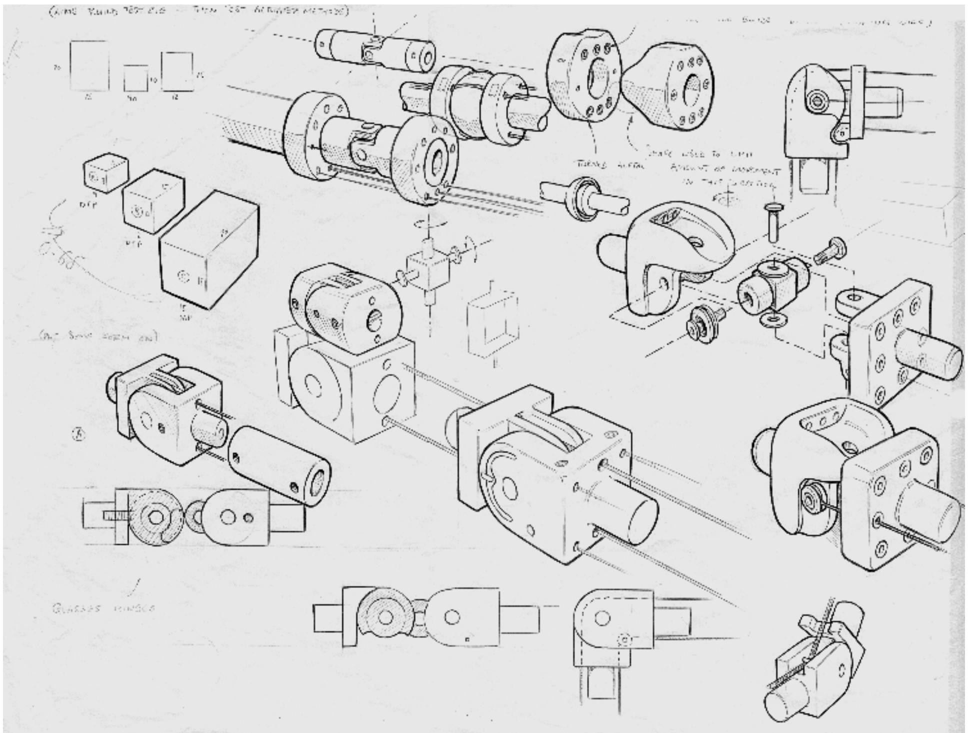
4. Development of Anatomically Analogous Metacarpophalangeal Joints and the Assembly of a Skeletal Model Hand



A Sketch Sheet Used in the Development of the Model MCP Joints

The development of a skeletal model hand continued with the study of the metacarpophalangeal (MCP) joints. These were developed to complete the joints necessary to assemble a model 'finger' for subsequent assembly into a model 'hand' as it was evident from the review of the model IP joints that a complete hand configuration was necessary to support the evaluation of the joints.

Sketch book idea development and observational drawing were used as integral part of the creative reasoning phase of the research activity. Additionally, in order to complete the assembly of a model hand joint principles elucidated from the creative reasoning process, focussing on the finger joints, were applied to the joints of the wrist.

This chapter starts with descriptions of articulations of the human MCP joint, for both a prosthesis and a robotic 'hand'. The articulations of the normal human MCP joint are then discussed. This is followed by details of the creative reasoning process applied to the development of analogous MCP joints. The principles deduced are then graphically represented along with their relevant sketch sheets. The application of previously elucidated principles to the development of a model wrist is then discussed.

With a model hand complete quantitative and qualitative evaluation of the joints was possible. This chapter finishes with the evaluation of the model hand and recommendations that were taken forward to the next cycle of development.

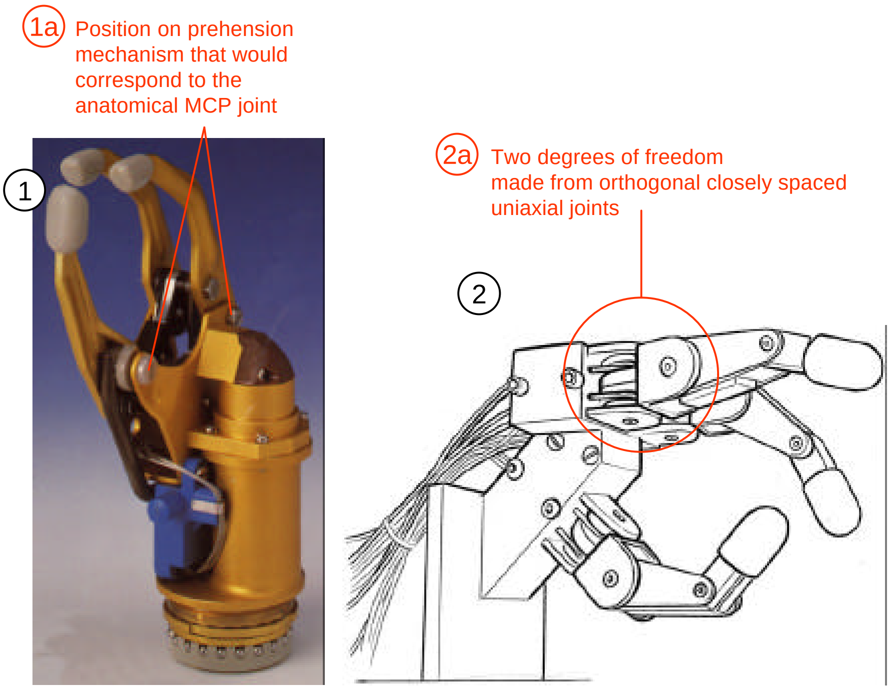


Fig 4.1 Prosthetic and Robotic Terminal Devices - Equivalent MCP Joints

Figure 4.1 (1) shows an Otto Bock prehension mechanism from a myoelectric terminal device. Its structure is so far removed from the structure of anatomical hand that it is difficult to assess an equivalent MCP joint. However, when this mechanism is covered by a cosmetic glove the articulations closest to the position of the MCP joints are indicated in the figure as (1a).

These articulations permit uniaxial rotations around the positions marked (1a). Positioning powered articulations at this point has been stated as allowing an optimal functional grip for a device that only possesses a single degree of freedom powered movement (Gow 2000).

The robotic hand shown in figure 4.1(2) is the JPL /Salisbury Hand (Rosheim 1994). It has joints at the base of each finger that combine to give articulations with two degrees of rotational freedom (Mason and Salisbury 1985)(2a). This robotics research showed that for optimal grasping and dextrous functions a hand configuration was needed that permitted two degrees of freedom at an equivalent position to the human MCP joint (Mason and Salisbury 1985).

The JPL/ Salisbury hand is mechanistic in appearance, therefore, to derive principles for an analogous MCP joint potentially combining form and function it was considered necessary to observe apply the creative reasoning process to the human MCP joint.

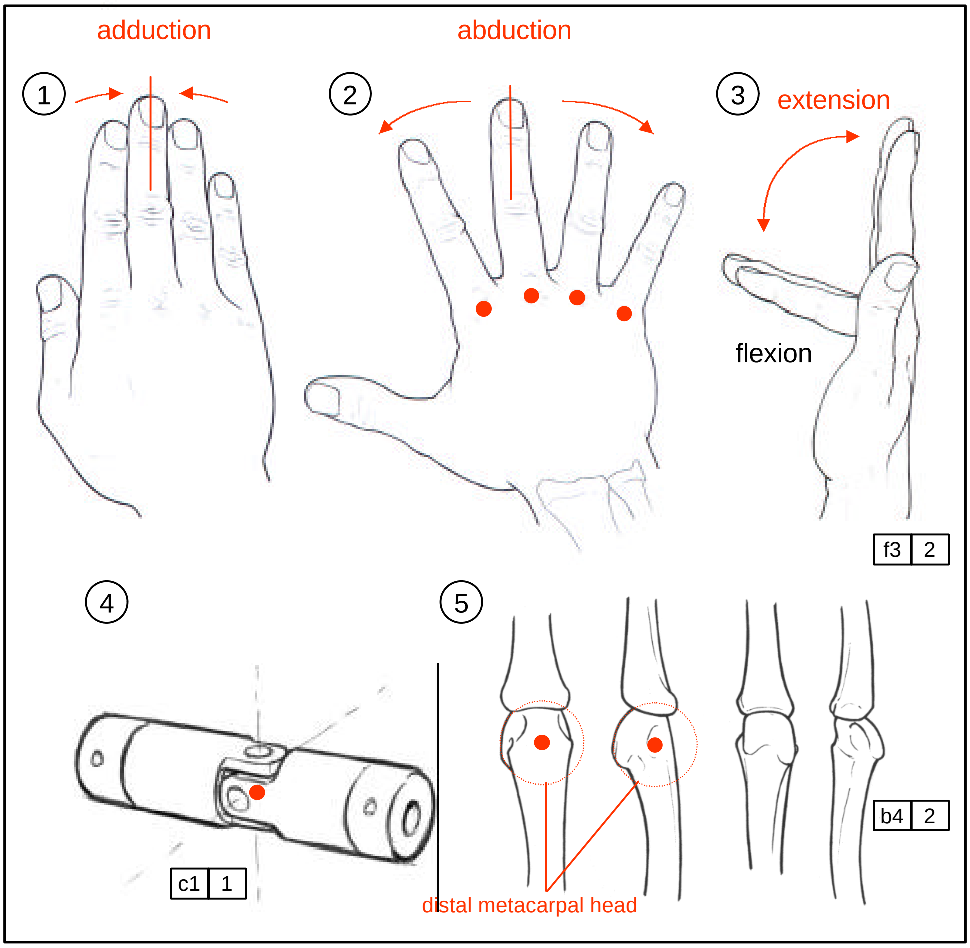


Fig 4.2 Metacarpophalangeal (MCP) Joint Movements

Anatomical literature states that unlike the the interphalangeal joints the metacarpophalangeal (MCP) joints can be actively adducted (1) and abducted (2) as well flexed and extended (3) (Kapandji1982, Williams 1998). A series of drawings of one of the researchers hands (1-3) were completed to examine these movements. This exercise highlighted that the movements of adduction / abduction and flexion / extension appeared to be around a single point at each joint (red marks). This type of articulation can be seen in a universal joint where two orthogonal axles cross on a single centre point indicated by a red dot (4). Previous researchers have likened the movements of the MCP joint to those of a universal joint (Youm et al 1978). However the appearance of the universal joint (4) differs from that of the MCP joints. Therefore, observational studies of the skeletal form of the MCP joint were undertaken to gain knowledge about what might be an appropriate form for an analogous joint. Sketch (5) shows this series of observational drawings, made from orthogonal view points, from skeletal three-dimensional anatomical models. These sketches showed that part of the form of the head of the MCP joint is approximately spherical. Therefore, it was considered consistent that articulations around a roughly spherical head would appear to be around a single centre point. Reasoning based on the spherical form of the distal metacarpal has also been used by (Hagert 1981) in deducing that the MCP joint has a single centre of rotation in planes of both flexion / extension and adduction / abduction.

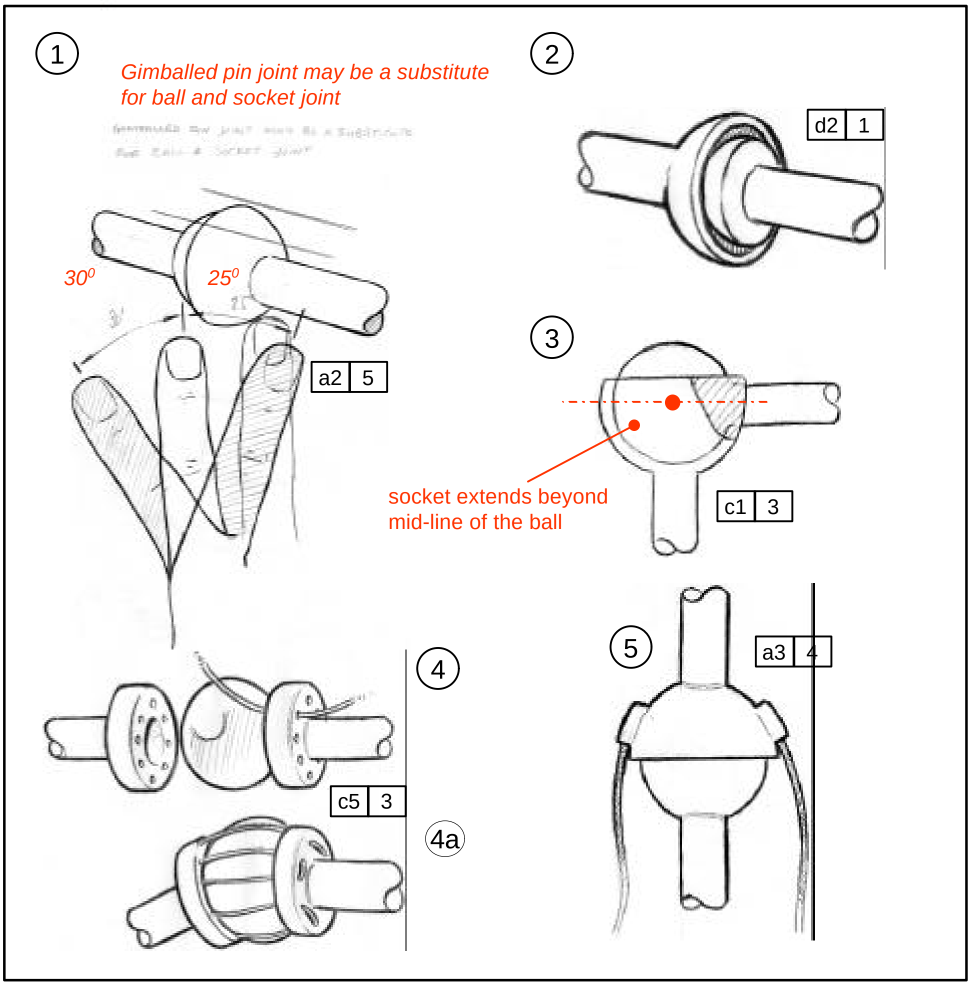


Fig 4.3 Ideas Generated from the form of the Head of the MCP joint

The observational studies of the spherical head of the distal metacarpal bone led to initial analogous joint ideas using a sphere as the articulating surface (1, 2). Initially, commercially available miniature ball and sockets joints were considered such as those often used in gear linkage systems. However, these components are connected together by the socket extending beyond the midline of the ball (3) which limits the range of movement. Whilst they allow a range of movement of approximately 30 degrees from centre, adequate for adduction / abduction (Daniels and Worthingham1986) (1), they would not permit the greater range a movement needed for flexion / extension (Daniels and Worthingham1986). To allow full flexion it would be necessary to remove some of the socket section (3). Sketching this removal of material indicated that the joint might be more likely to dislocate, therefore, sketches were completed to investigate how the joint might otherwise be constructed. Sketches (4) and (4a) explored the use of elasticated thread to join the components. However, these ideas were discounted as it was considered that the joint would then spring back to the neutral position, which does not occur in the human joint. A second idea of placing inextendible ties on the medial and lateral sides of the joint was sketched (5). However, this was also discounted as it would prevent adduction and abduction movements. The annotations on sketch (1) demonstrate that as with the interphalangeal joints pinned joints were being considered as a more practical analogy.

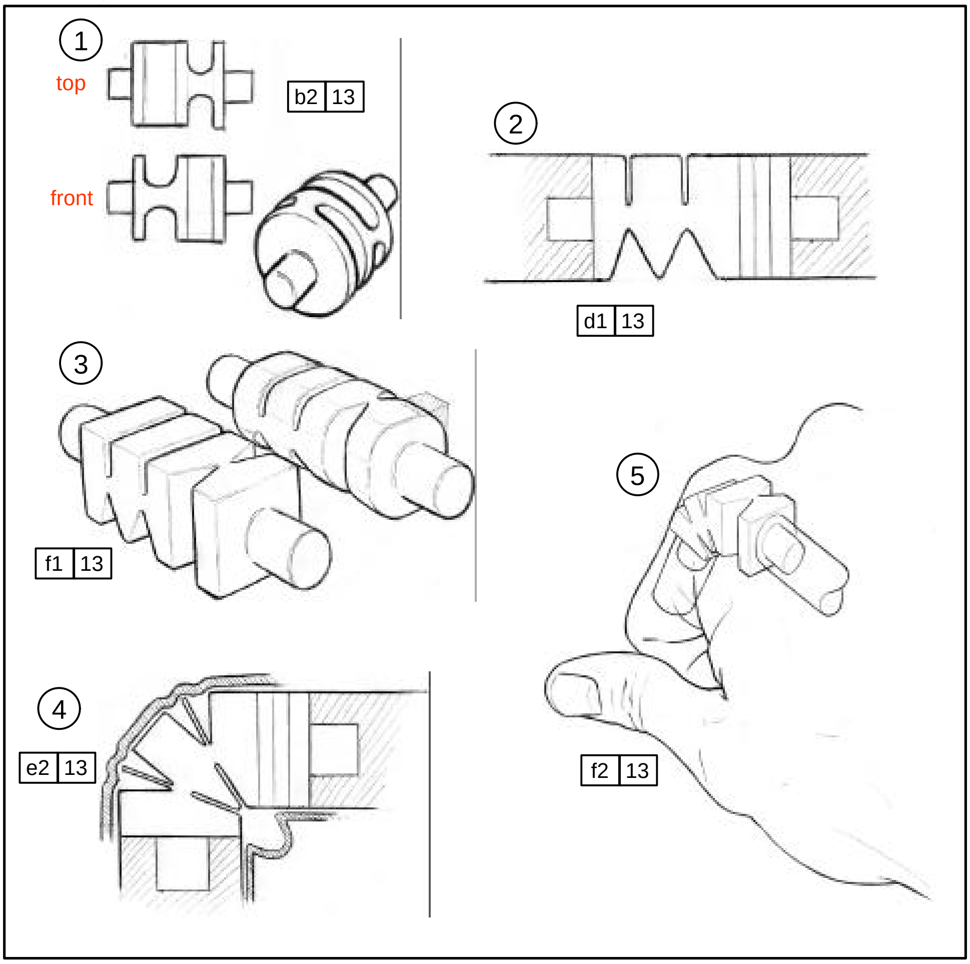


Fig 4.4 Single Piece Hinge Ideas

The relatively complex sketches of the previous page highlighted the need for simpler designs more appropriate for economic manufacture, as cost has been indicated as a major factor in the acceptance of a new prosthetic device (Aghili and Meghdari 1995, Gow 1993) . Consequently, several ideas were drawn that aimed to produce a joint design from a single moulded polypropylene component. Sketch (1) shows how the orthogonal movements of flexion / extension and adduction / abduction might be achieved by producing orthogonal reductions in the thickness of a cylindrical component. This sketch indicated that although a single reduction in the thickness might allow the complete range of motion for adduction and abduction movements it might not permit complete flexion and extension movements. Sketch (2) shows how a series of changes might remedy this. Sketch (3) details how such a simple design might easily be manufactured with a roughly circular cross-section, similar to the human finger (Landsmeer 1976) adding to its cosmetic appearance. By visually exploring the flexed joint it was though necessary to include thin fins to prevent a cosmetic glove being caught in the joint as it opens on flexion (4). Sketch (5) was completed to determine the approximate scale of the joint. From this exercise it was concluded that the articulations of flexion / extension, adduction / abduction might be too far apart to produce a cosmetic movement. Additionally, it was considered that the concerns of torsional stability found in the development of the interphalangeal joints would be amplified by a series of reductions in thickness required for ranges of movement of the MCP joint.

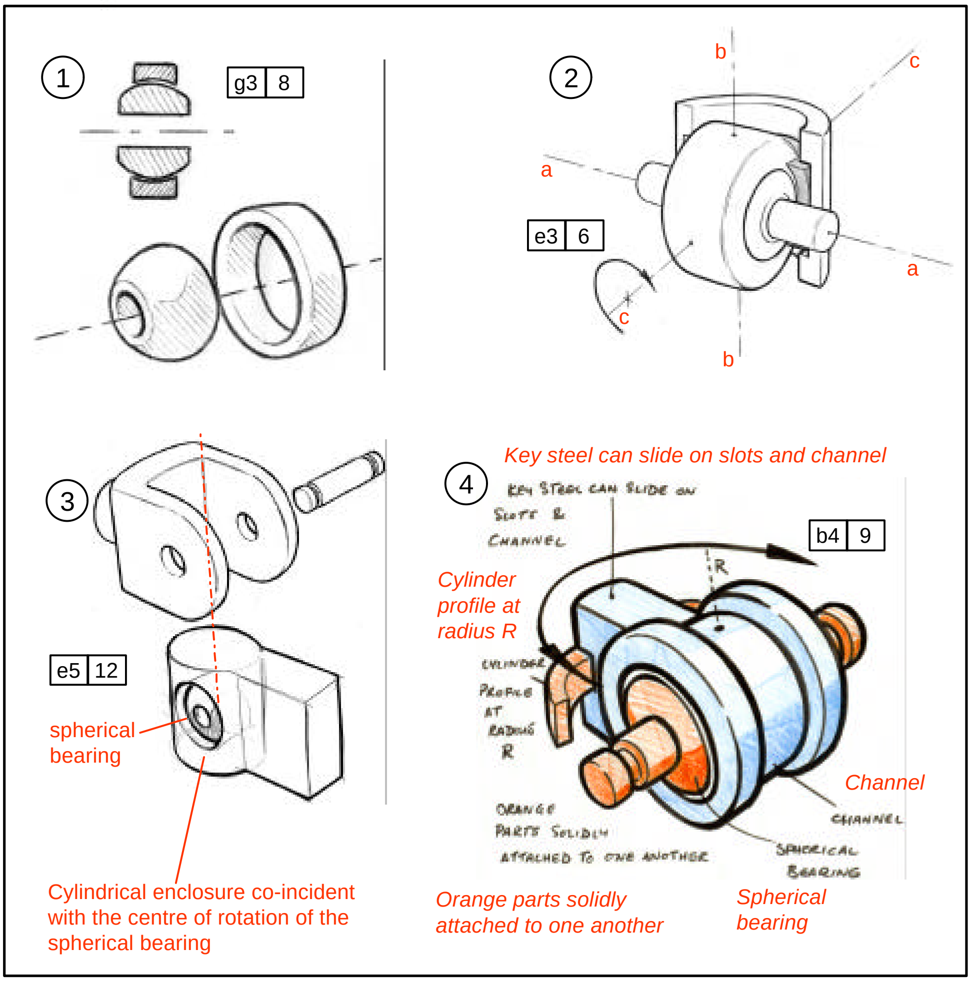


Fig 4.5 Spherical Bearing - Constraint of Rotational Freedoms

In addition to commercially available ball and socket components, spherical plain bearings were considered as components for an analogous MCP joint. This was both due to their ready availability at miniature sizes and also their ability to support relatively large static loads, both rotationally and axially without dislocating. Sketch (1) shows both an exploded view and a cross section of a plain spherical bearing. Spherical bearings are usually made from low friction alloy steel and are commonly found at the ends of pneumatic/hydraulic actuators. They are able to rotate in three orthogonal planes (2). However, from the observational drawing and literature review (Kapandji 1982) it was considered appropriate to limit the rotational freedoms to two, in the planes of flexion / extension (2 a-a) and adduction/abduction (2 b-b).

Using the spherical bearing in the orientation shown in sketch (2) allows for a large range of movement around the axis of flexion/extension (a-a) and limited rotational movement in axis of adduction/abduction (b-b), similar to that of the human MCP joint (Daniels and Worthingham 1986). Two ideas were considered to constrain the third axis of rotational freedom (2 c-c). These included producing a cylindrical enclosure coincident with the rotation centre of the spherical bearing (3); with its long axis running in the axis of adduction/abduction. The second idea focussed on the use of two orthogonally placed pieces of key steel (4).

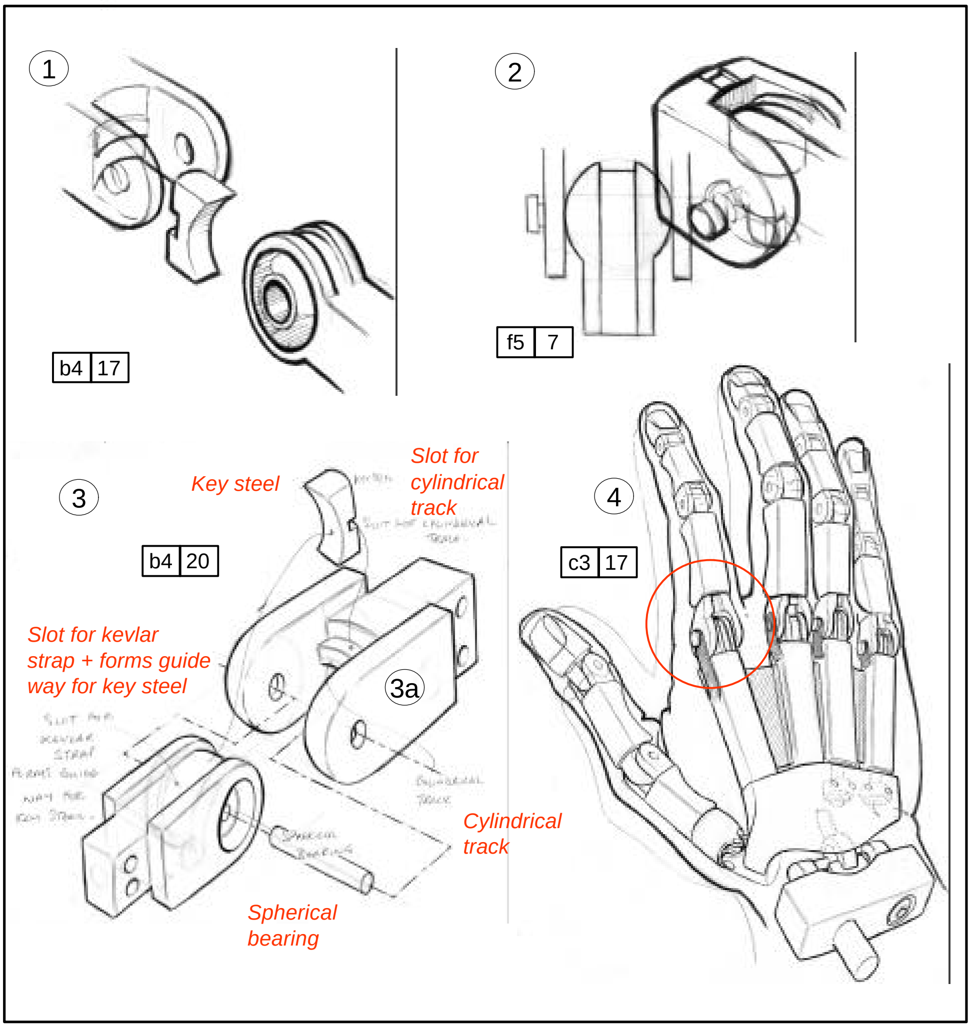


Fig 4.6 Spherical Bearing 2 - Constraint of Rotational Freedoms Cont.

The two means of constraining the rotational degrees of freedom of the spherical bearing were incorporated into analogous joint designs (1, 2). Sketch (3) shows how the guide channel for the key steel, required to constrain the joint, could also be used to guide an analogous tendon, and how a cylindrical track, again required for constraint, could be combined into the distal component (3a). In addition to detailing the enclosures around the spherical bearing, sketch (4) shows how drawings were completed to ascertain the relative scale of the joint when placed in the configuration of a human hand. From this exercise it was determined that the cylindrical idea (2) may be more productive than using the sliding key steel. It was envisaged that the material for the majority of the joint would be a bearing plastic, and it was foreseen that rotational forces transmitted to the key steel from the remainder of the finger would deform the bearing plastic track. The cylindrical constraint form of sketch (2) was chosen in preference as it was considered that torsional forces would be spread over a larger area.

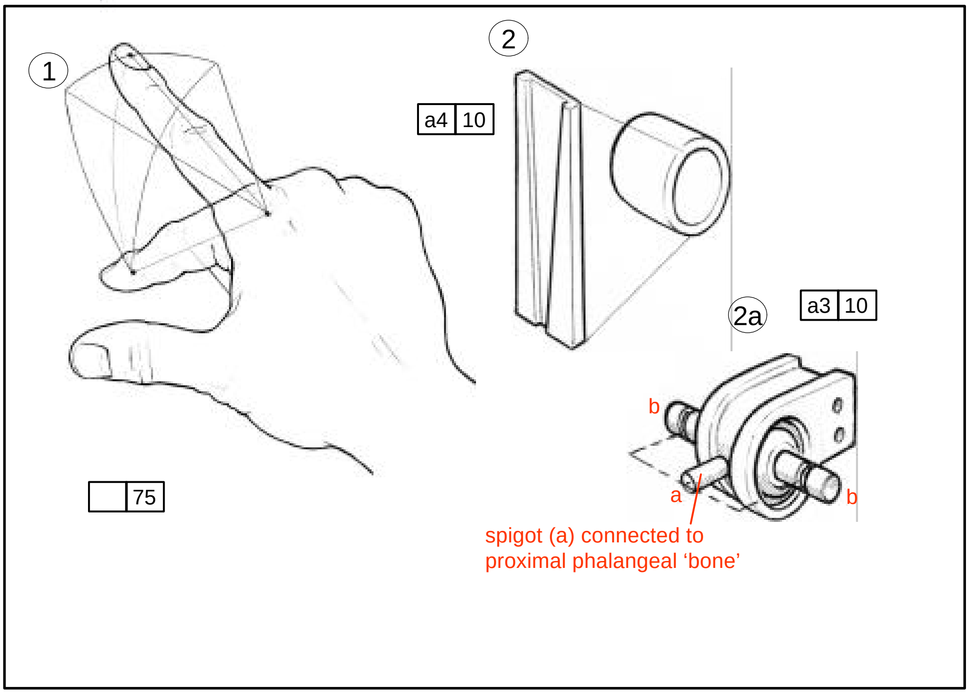


Fig 4.7 Spherical Bearing - Progressive Constraint

From observational drawing of one of the researcher's hands and reference to research studying the function of the hand (Williams 1998) it became apparent that the range of movement of the MCP joint in the plane of adduction / abduction diminishes as the joint is flexed (1).

In the neutral position the range of adduction / abduction movement is maximal, whereas with the interphlalangeal joints extended and the MCP joint fully flexed there are no discernible adduction/abduction movements (Williams 1998). Two ideas were considered to approximate this progressive constraint.

The first idea focussed on a tapering groove projected onto the cylindrical surface of the distal metacarpal component (sketches 2 & 2a). With a spigot (a) connected to the proximal phalangeal component through the axle (b-b), to progressively constrain lateral movement as the joint is flexed.

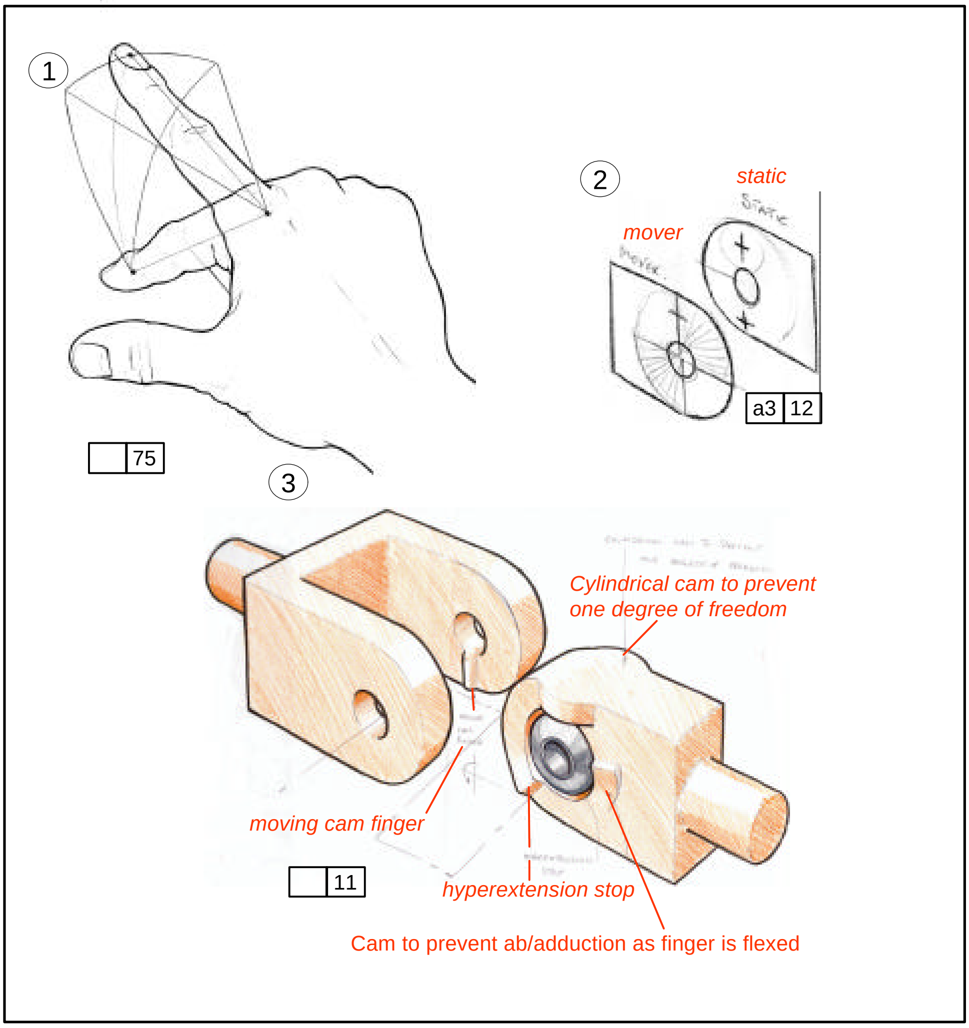


Fig 4.8 Spherical Bearing - Progressive Constraint (cont.)

A second idea resulted from consideration of the lateral and medial sides of the joint design. It was considered that for a 90 degree flexion movement there will be a unique quadrant that can be used as a cam surface (2).

This idea was explored in sketch (3). When the joint is in the neutral position a cam ‘finger’ connected to one side of the joint is aligned with the cylindrical cam allowing maximal adduction/abduction, whereas at full flexion the cam finger contacts with a cam on the opposite component to prevent lateral movement.

This concept was preferred to the spigot concept of the previous page as maximal lateral constraint coincides with a maximum ‘moment arm’ between the cam finger and distal metacarpal component.

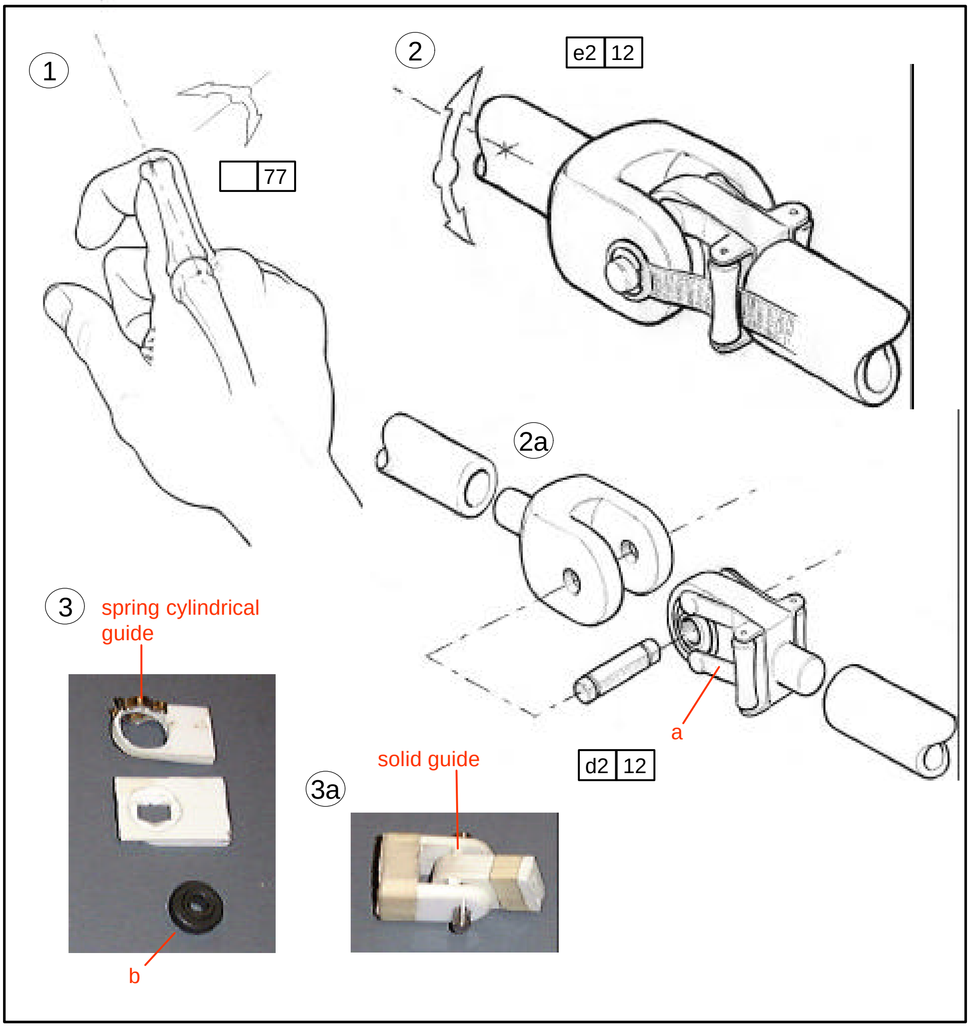


Fig 4.9 Spherical Bearing - Sprung Constraint

Further observational drawing (1) combined with palpation of one of the researcher's fingers, revealed passive axial rotation was possible at the MCP joint.

Palpation demonstrates a sprung quality to this movement, returning the finger to the neutral position. In attempting to mimic this action the solid cylindrical cam was replaced by a spring steel guide (a) shown in sketch (2a).

Both the solid cylindrical cam (photograph 3a) and the sprung steel idea (photograph 3) were prototyped from a lightweight polystyrene material. This exercise showed that although both ideas appeared promising for further prototyping, the weight of the metallic spherical plain bearing might make the joint ideas too heavy for application in a future prosthetic hand.

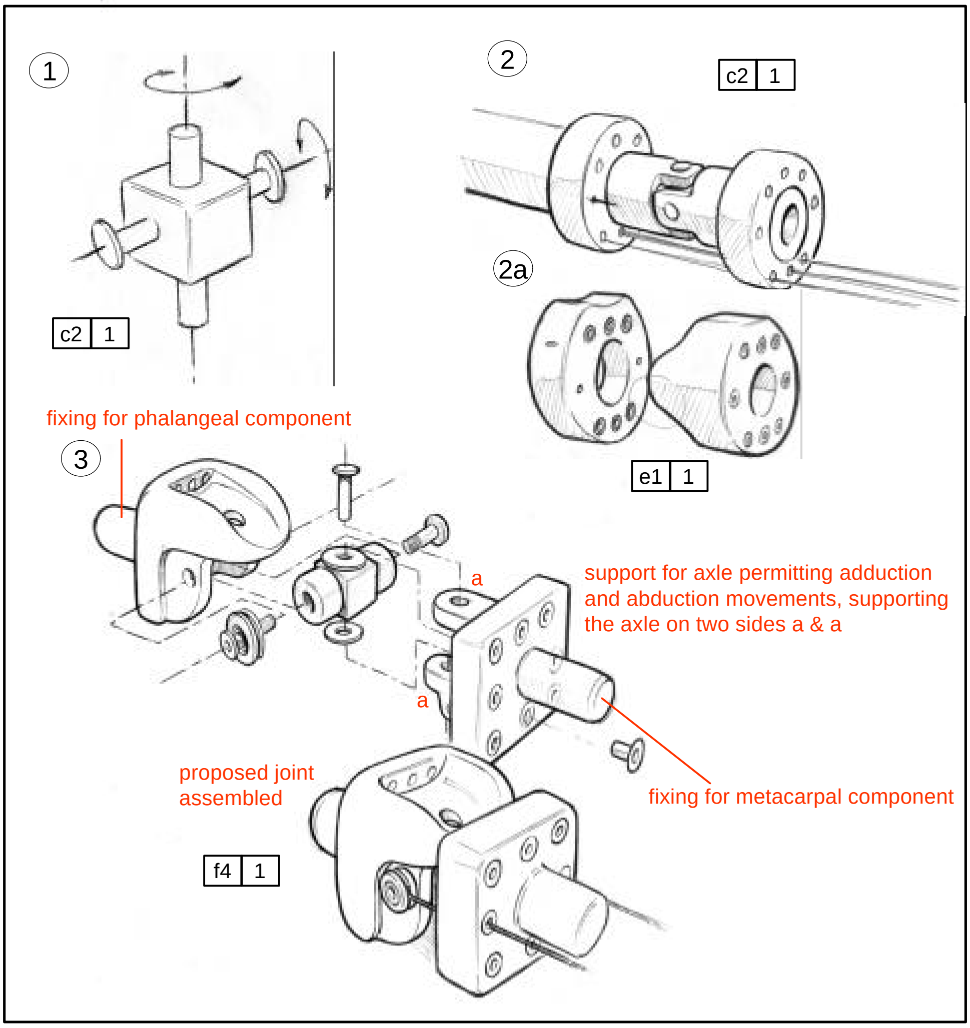


Fig 4.10 MCP Articulation Based on Universal Joint Principles

It was concluded from the spherical bearing prototypes that weight considerations dictated that steel components should be minimal. Therefore, further sketch ideas were based on the universal joint, as the function of this type of joint relies on orthogonal axles rather than bulky steel forms (1).

Initially, joint ideas were based around commercially available miniature components. From further sketchbook development it was evident that collars might need to be fitted to the joints for guidance of analogous actuating tendons, and to provide constraint for the ranges of movement (2, 2a).

The extent of the proposed modifications indicated that a specifically designed joint was justified. Sketch (3) shows how mechanical fixings were suggested both as a means of connecting either side of the joint and also to act as the axles around which the joint would articulate.

Initially, as in (3), the orthogonal axles were to be supported on either side of the joint form (a-a) (3). However, it was found from measurement of readily available miniature fixings that this would make the joint too bulky. Therefore, further joint ideas were developed using a cantilever support for the articulation of adduction/abduction.

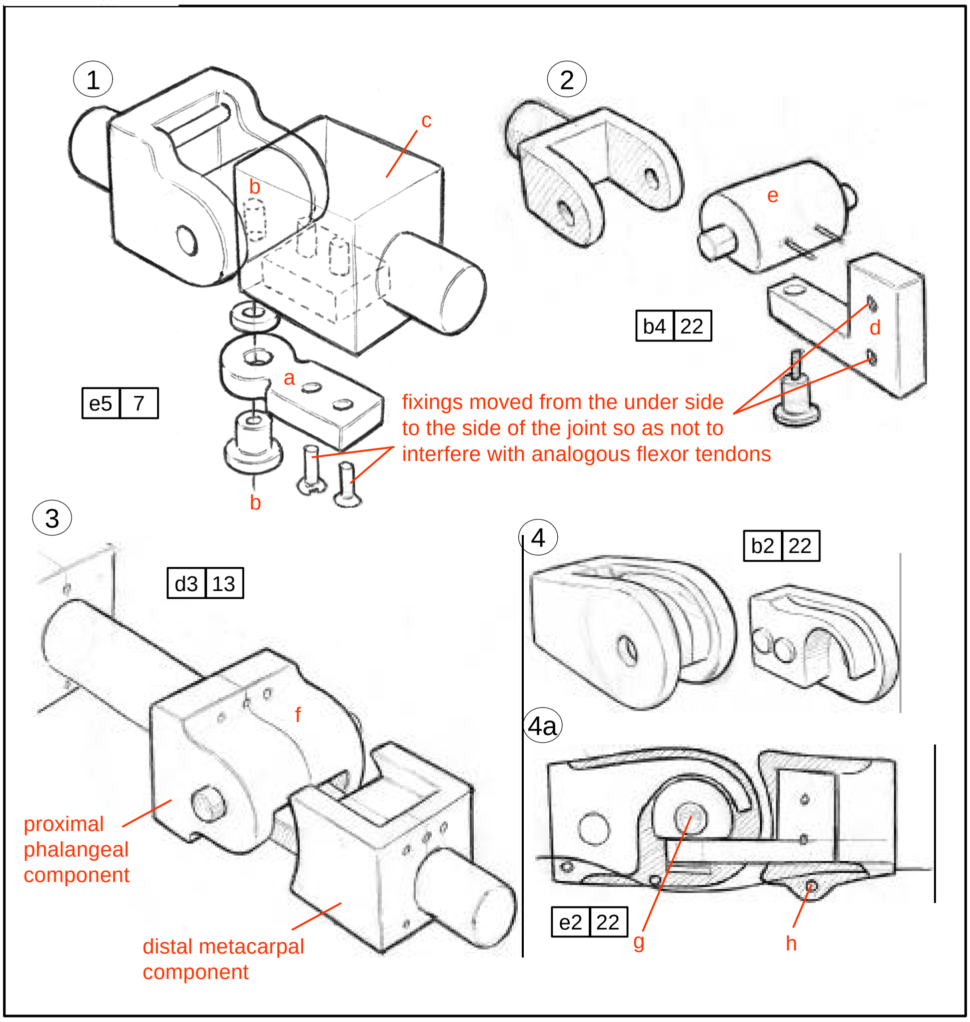


Fig 4.11 Universal Joint Ideas

Sketch (1) shows that initially a simple plate design (a) was considered as the cantilever support for the adduction / abduction axis (b-b). However, it was thought that using mechanical fixings to join this to the distal metacarpal part of the joint (c) might interfere with the guidance of analogous flexor tendons. Consequently, component (d) in sketch (2) shows the cantilever support as an 'L' shape where the fixings are on the sides of the joint.

Iniitally, the axle for flexion/extension was drawn as large component, to present a smooth surface over which analogous flexor tendons could pass (e) (2). However, with reference to weight it was considered inappropriate, instead it was considered better for the tendons to pass over a bearing plastic enclosure (f) (3).

It was proposed that this enclosure be made in two halves to fit onto the sides of the the flexion / extension axle (g) (4a), and that in a future manufactured item the sides of the bearing plastic component be ultrasonically welded together.

Sketch (4a) proposed that guidance pins for an analogous flexor tendon (h) could be trapped in a sandwiched design in a similar manner to those guiding the analogous flexor tendon in the interphalangeal joints.

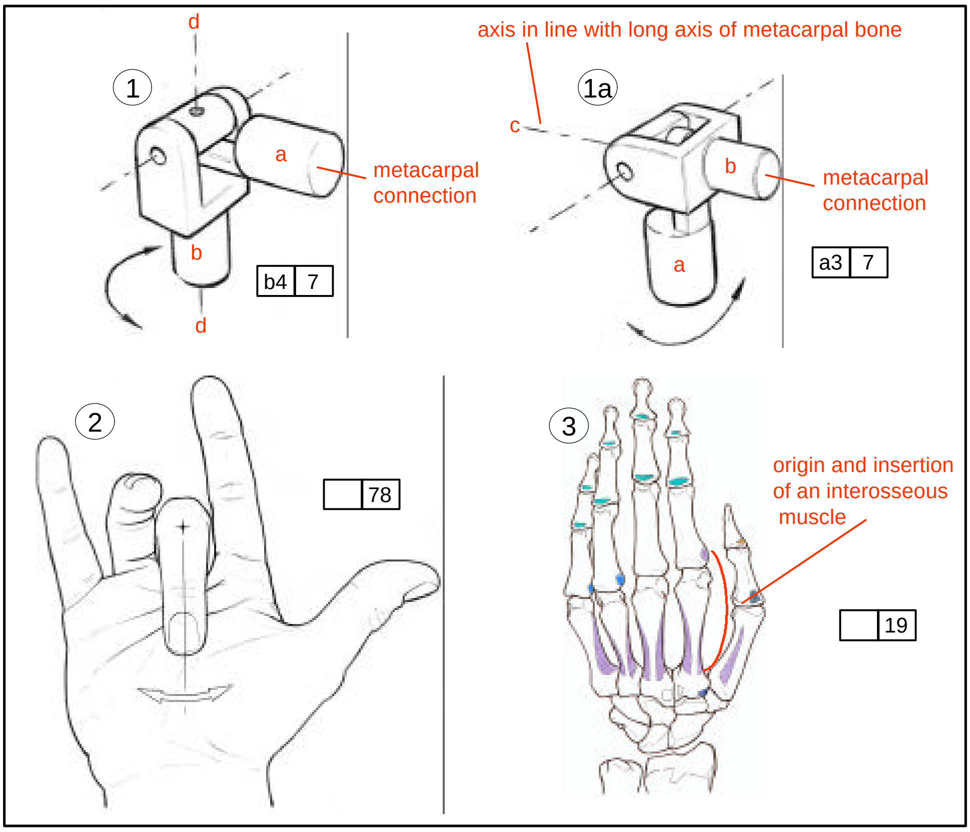


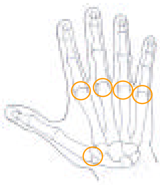
Fig 4.12 Universal Joint Ideas - Orientation

Once the basic form of the axles was decided, the articulations were visually tested in sketches (1, 1a). From this exercise it was found that exchanging component (a) and component (b) on the distal end of the metacarpal section would result in very different articulations at full flexion.

In the neutral position both configurations would have similar articulations, however, when fully flexed the configuration in sketch 1a would possess a lateral articulation in line with the long axis of the metacarpal bone (c); unlike sketch (1) that still rotates along axis (d-d).

To identify which configuration represented the closest analogy, one of the researchers hands was palpated. On flexing the middle finger it was clear that an active adduction/abduction motion was possible, similar to that of permitted by axis (d-d) (1).

Further observational drawing was completed to understand more about the interossei, the intrinsic musculature of the hand that actuates the adduction / abduction movements of the fingers (Kapit and Elson 1993). These were done from three-dimensional anatomical models marked with the ‘origins’ and ‘insertions’ of the interossei, and these were sketched in purple (3). From this exercise it was determined that the axle configuration in sketch (1) would be the closest analogy as the position of the interossei appeared to give no mechanical advantage to produce the movements of sketch (1a).



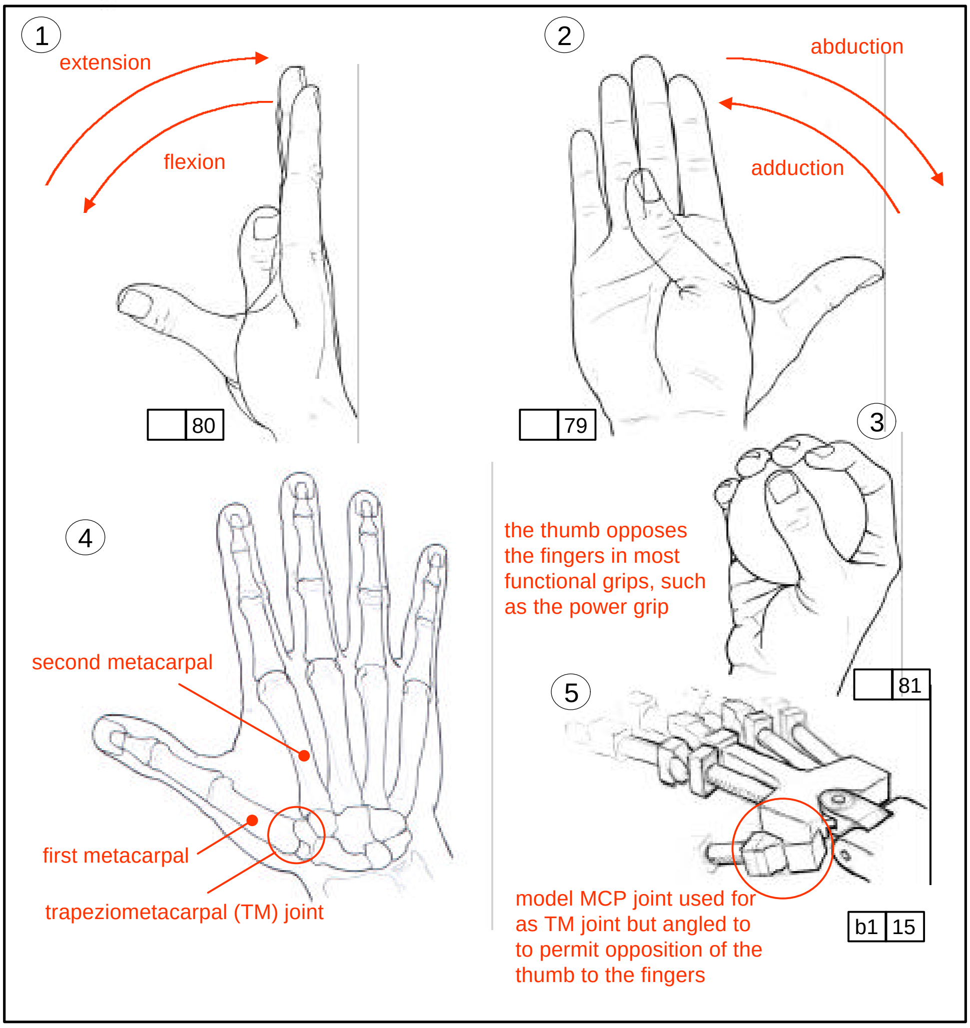
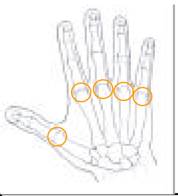


Fig 4.13 Orientation of the Universal Joint for a Trapeziometacarpal Joint

A literature review indicated that the trapeziometacarpal (TM) joint of the thumb possessed articulations that could be considered as similar to the joint form proposed for the analogous MCP joint (Cooney et al 1981). This allows movements of flexion and extension (1) and adduction/abduction (2) (Kapit and Elson 1993).

To achieve, opposition (3) and other functional movements (Kapandji 1982) it was necessary to angle the axes of the joint relative to the plane of the palm (Conney et al 1981). Therefore, it was considered that the proposed MCP joint was appropriate to use as a TM joint to achieve the range of movement of the thumb, only the joint should be angled to the palm. Measurements were taken from the intact hand of one of the researchers to determine the angles of orientation of the model joint necessary to enable the MCP joint to function as a TM joint. This was done using goniometric techniques to measure the angle between the first and second metacarpal shafts (4) both in the frontal and sagittal planes when the hand was relaxed. It was found that the first metacarpal was approximately abducted 40 degrees from the second metacarpal in the frontal plane, and flexed 30 degrees in the sagittal plane (5).



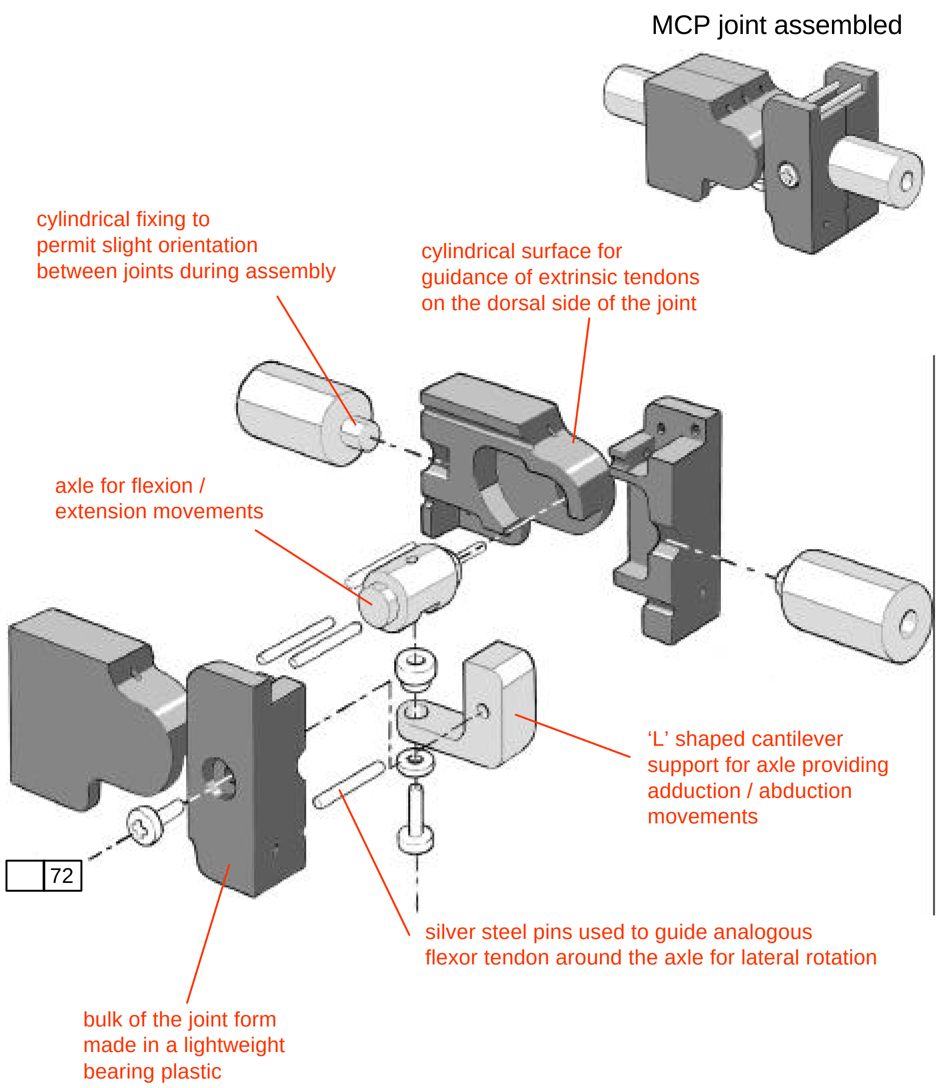
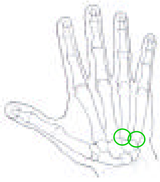


Fig 4.14 The Analogous Model MCP Joint

The figure above shows an exploded view of the model MCP joint, labelled with the design principles embodied within this design.



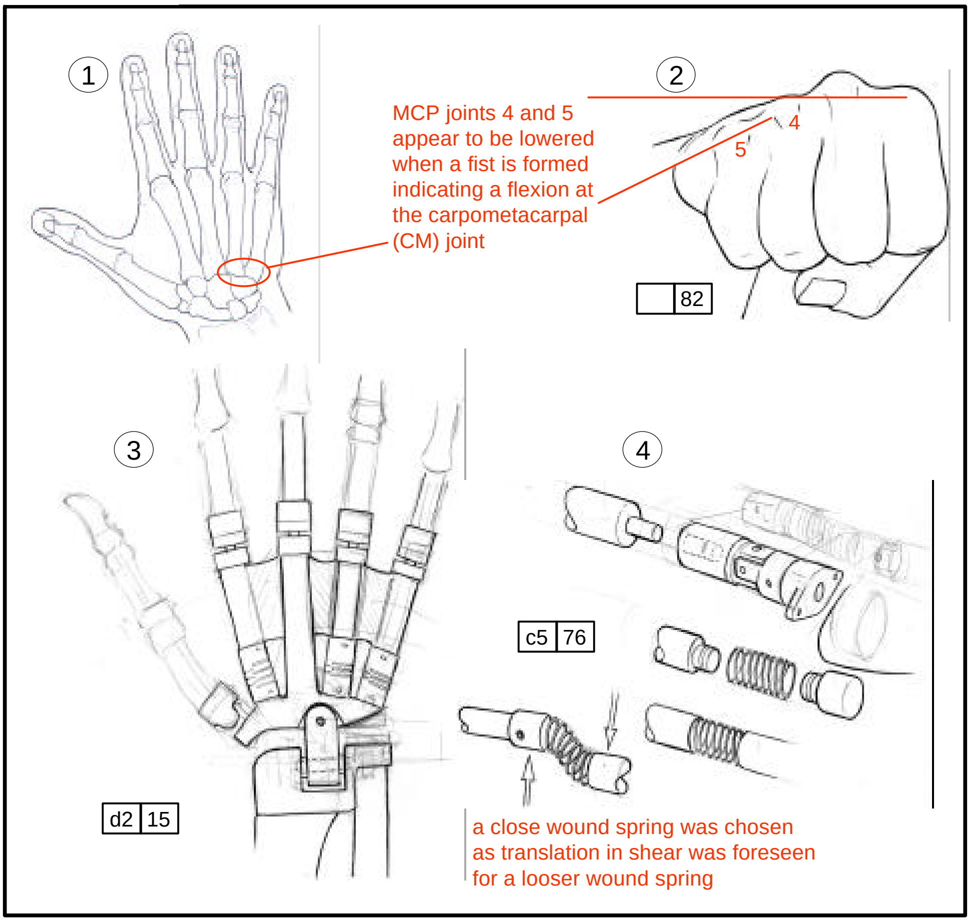


Fig. 4.15 Carpometacarpal Joints Development

From observation and palpation of intact hands it was concluded that the range of movement of the last two digits (four and five), are effected by the position of the more proximal joints, the carpometacarpal (CM) joints (1). This finding was verified against anatomical literature (Kapandji 1982, Landsmeer 1976). It appeared from palpation that these joints possessed two degrees of freedom in flexion / extension, and adduction / abduction. The action of the joints on the hand appeared most marked when making a fist. The MCP joints of digits 4 and 5 appeared to flex, lowering them from their previous position, approximately in line with MCP joints two and three (2). Again this was verified against anatomical literature and found to be a normal action of the hand (Landsmeer 1976).

The CM joints of digits 4 and 5 appeared to possess 'sprung' action, unlike the MCP joints, returning them to a neutral position. Consequently, use of the designed MCP joint design at this point appeared unsuitable. Instead, simple ideas using a spring as an initial approximation of this joint were considered. It was thought that placement of a close wound extension spring in line with the long axis of the finger would permit the small angular changes that were observed, whilst positively returning the joint back to a neutral position (4).

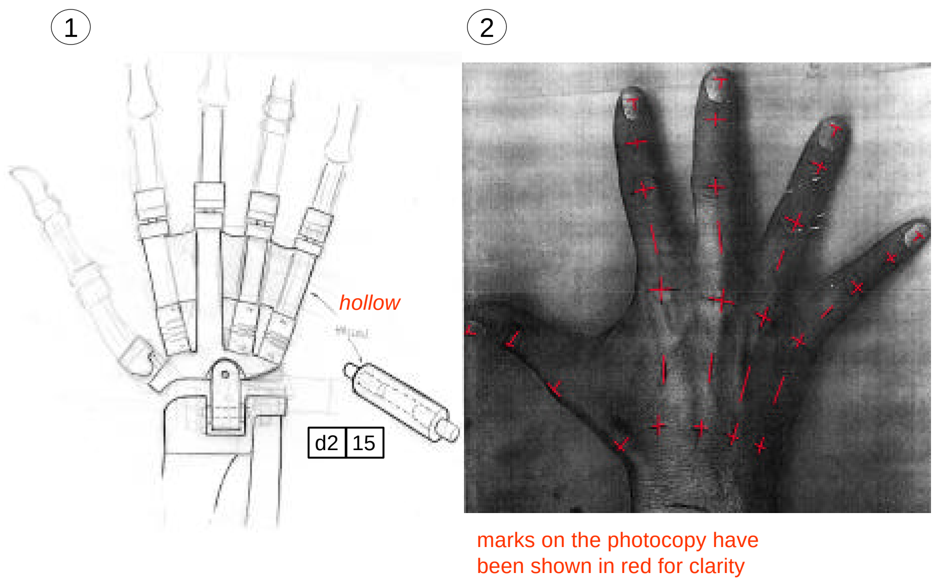
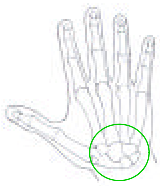


Fig 4.16 Strut Development

In the development of the IP joint it had been considered appropriate to provide a cylindrical bore in either end of the joint to provide a fixing method that would permit the joints to be slightly angled relative to one another. For similar reasons a cylindrical fixing method was chosen for the MCP joints.

The struts between joints must not only maintain both the relative angle and distance between the joints, but also be lightweight so not to detract from the lightness of weight of the joints in evaluation. Therefore aluminium tube was considered appropriate, possessing rigidity over the short spans required and being light in weight. The cylindrical section also permitted the joints to be slightly rotated relatively to one another along the long axis of the tube (1).

The necessary lengths of the aluminium struts were determined for the model from a photocopy of one of the researchers hands, which had been palpated and marked with the apparent joint centres (2). The lengths of the proposed joints was subtracted from the lengths between centres to determine the strut lengths needed.



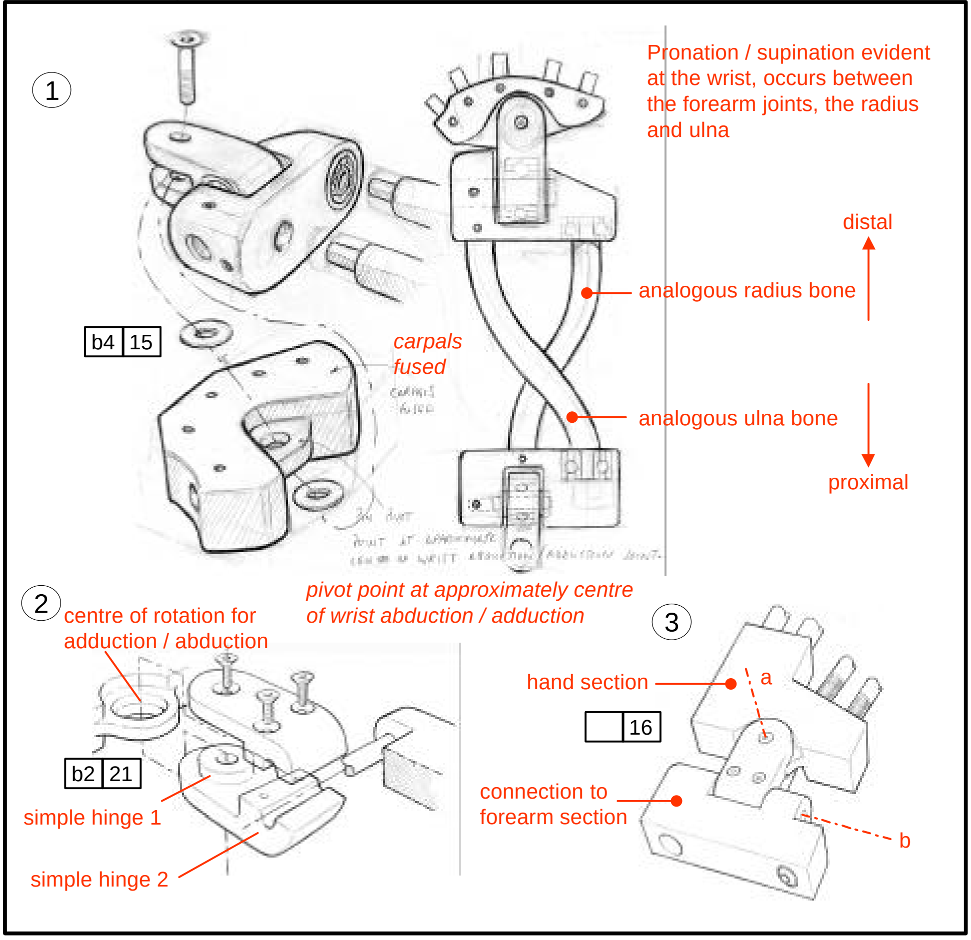
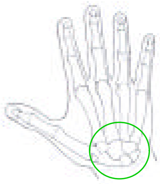


Fig 4.17 Mk1 Wrist

With designs for the IP, MCP amd CM joints it appeared that the only joint remaining before the assembly of a skeletal model hand for review was the wrist. One of the researchers hands was palpated and it appeared that this joint permitted two degrees of freedom, in the plane of flexion / extension and adduction / abduction. This was found to be consistent with anatomical literature. (Kapandji 1982). However, it was noted that positioning of the hand relies on a third rotational degree of freedom in line with the long axis of the forearm termed pronation and supination movements (Kapandji 1982). Review of the skeletal anatomy at an anatomy teaching laboratory indicated that pronation / supination was not achieved through articulations at the wrist, rather between articulations at the distal and proximal ends of the forearm (1). Again this was reviewed for validity against anatomical literature and found to be consistent (Kapandji 1982). Therefore, a decision was made to only provide articulations for adduction / abduction and flexion / extension within the model wrist. The apparent centres of the articulations were determined from palpation of one the researchers hands and marked on the skin. The centres of rotation appeared separated. The centre of rotation in the plane abduction / adduction being more distal than that of flexion extension (2). Therefore, it was considered that simple hinge joint principles such as those used for the IP joint could be used for the articulation of the wrist. Two joints were required with their axes of movement separated orthogonally (3 a,b). The ranges of movement of the wrist were taken from anatomical literature and use in the design of the two joints (Daniels and Worthingham 1986).



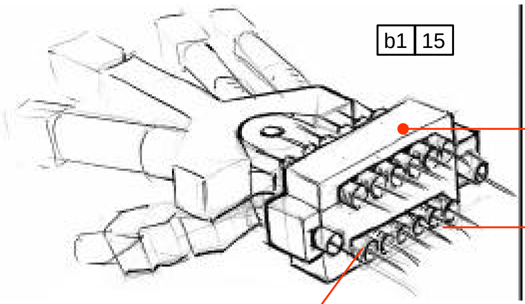
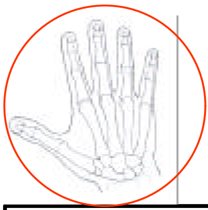


Fig. 4.18 Mk1 Wrist

The extrinsic extensor tendons to the fingers are guided through the anatomical wrist by the extensor retiniculum (Kapandji 1982). It was noted from anatomical texts that this appeared to be at approximately wrist level (Kapit and Elson 1993). Therefore, it was considered appropriate to provide guidance for the wire tendons motivating the fingers of the mechanical analogy at a similar level. It was thought advantageous to provide a method to increase the radius of curvature of the passage of the tendons through the wrist to limit friction effects, and a possible tendency the tendons might have to 'dig in' to the structure of the wrist guide. Extension springs were included in the guidance structure of the wrist to provide this increased curvature.



Arrangement into the Form of a Skeletal Hand

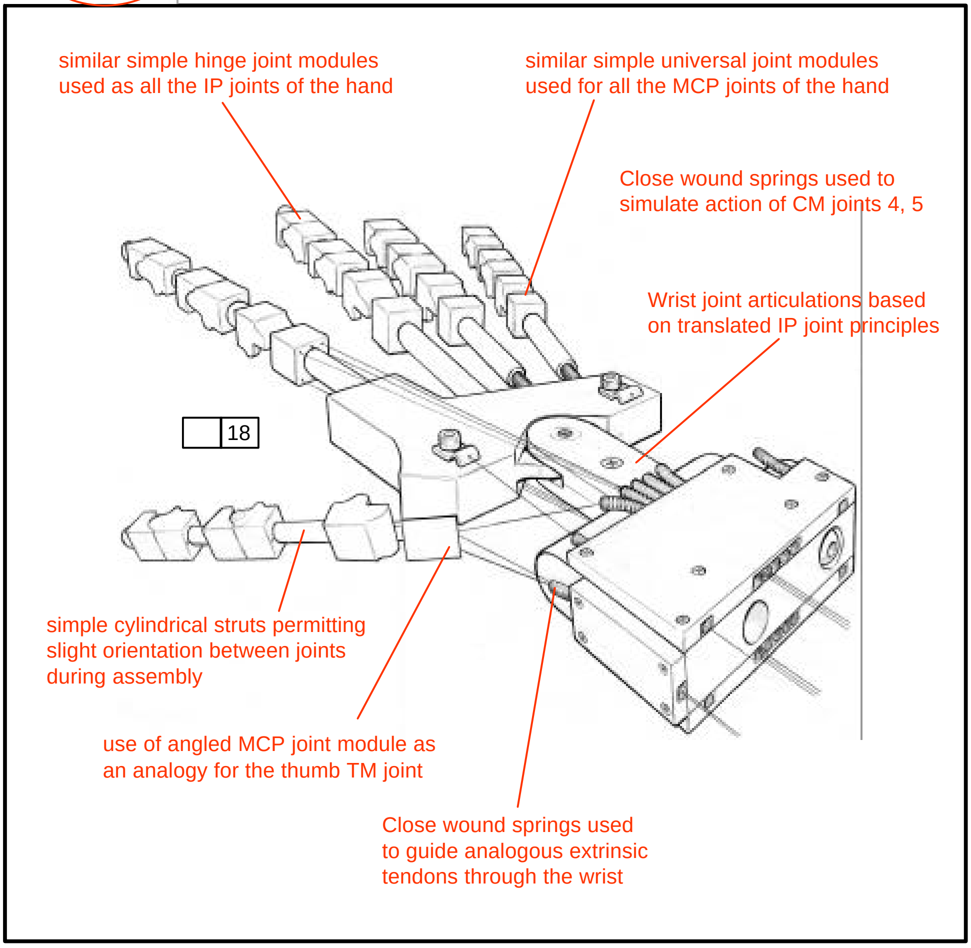


Fig. 4.19 Drawing Showing Joints Assembled into a Skeletal Hand Form

This drawing was made prior to the assembly of the finger joints and wrist section into a 'hand'. It shows the angled placement of the MCP joint used as a TM joint for the thumb, and the use of extension springs to guide the wire tendons from the fingers through the wrist.

This pictorial plan was done to to ascertain whether the designs could practically be combined with the IP joints at an appropriate scale to produce a convincing skeletal hand form. It was considered from this exercise that the individual components could be assembled convincingly. Therefore, detailed engineering drawings were made of the proposed MCP and wrist joints proir to prototype production. These were made both using traditional drafting techniques and CAD software.

Fig 4.20 Jigs for Machining of CNC Joint Forms

The detailed drawings were subsequently used to programme a CNC machine tool. In a similar manner to the manufacture of the IP joints, multiples of the MCP joint forms were machined in a single sequence.

Like the production of the IP joint, the MCP joints required jigs to be made using CNC to ensure accuracy for subsequent conventional machining. Due to the extra degree of freedom of the MCP joint its form is more complex, this resulted in consequent added complexity in the arrangement of jigs and holding fixtures.

Prototype production of the wrist was also completed using these techniques.

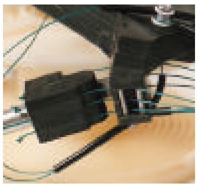
The skeletal model hand has been designed to be the same scale as the average human hand.

Because it is anthropometrically similar to the human hand it can be configured around many domestic products based on anthropometric constraints.

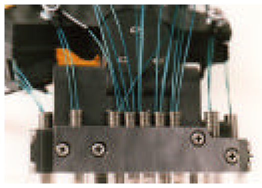
The hand is of modular construction and can be changed in size by altering simple interconnecting struts

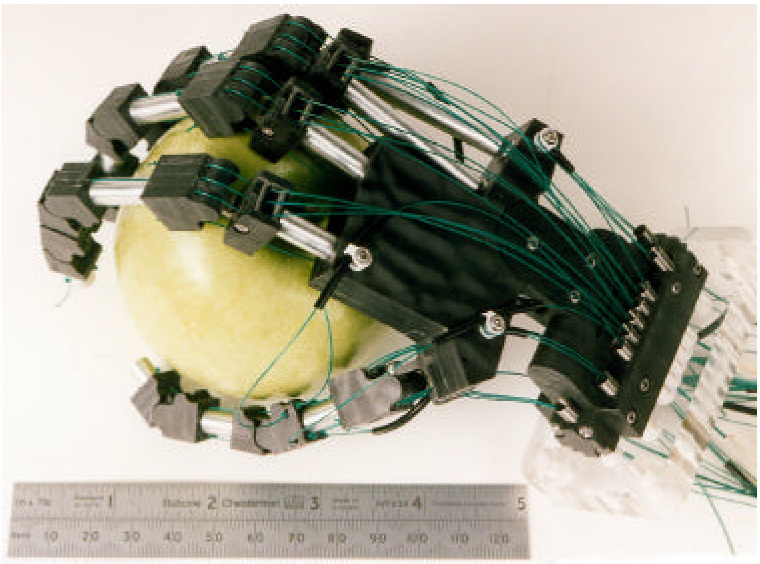
all the IP joints are of the same modular design

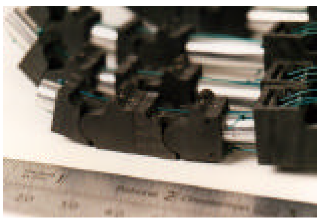
all the MCP joints are of the same design - the thumb TM joint is also an MCP module



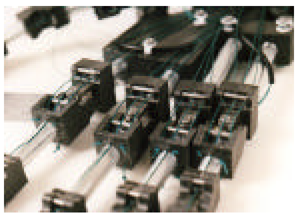
The model has an two degree of freedom articulated wrist which the analogous extrinsic tendons pass through





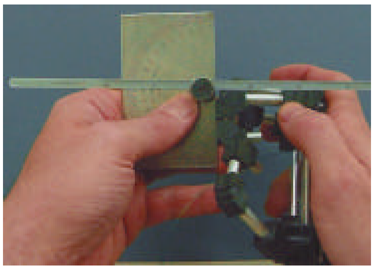


analogous extrinsic flexor and extensor tendons used to flex and extend the finger joints - additionally tendons activate movements of the wrist



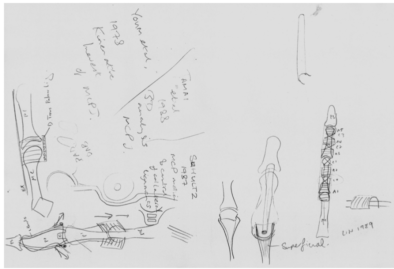
silver steel pins guide the analogous tendons around the joints to prevent bowstringing

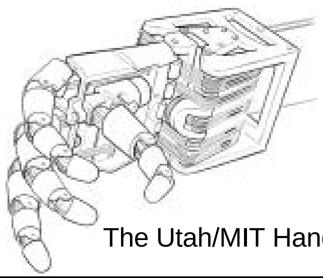
Fig 4.21 Design Principles Embodied Within the Skeletal Model Hand



Goniometric measurement

Qualitative Evaluation by Experts in the anatomy of the Hand (Detail of sketches performed by evaluator of the model hand)





The Utah/MIT Hand

Comparisons with the kinematic arrangements of robotic hands

‘End-user’ Focus Group

Fig 4.22 Evaluations for the Skeletal Model Hand

The assembly of the skeletal model hand provided the possibility for a wide review of the design joints and the design principles embodied within the model.

To assess the joints it was considered appropriate to use goniometric techniques similar to those used to assess joint range of movement in the intact hand (Norkin and White 1995). A ‘pretensioning jig’ was also constructed to evaluate the extrinsic actuation of the model.

It was proposed that the ‘closeness’ of the analogy of the joints to the human joints could additionally be assessed by qualitative methods. It was envisaged that this could be performed by experts in the anatomy of the human hand through visually assessment and palpation the model hand.

Additionally, it was thought that the model hand had reached a level of completion where it could be compared with the kinematic design of previous robotic hands. Although, it was recognised at this stage that the model lacked actuation of the joints.

The completed hand also provided the opportunity to extract valuable criticism on the model from prosthesis ‘end-users’. It was hoped this evaluation might indicate how the design principles within the model might benefit a future prosthesis. The groups chosen as end-user’s were primarily amputees but also include prosthetics, occupational therapists and a prosthetics manufacturer.

WRIST

Wrist flexion (degrees)
Model
90
Human
85

Wrist extension (degrees)
Model
45
Human
85

Wrist abduction (degrees)
Model
30
Human
15

Wrist adduction (degrees)
Model
43
Human
40-45

Values for human joints taken from Kapandji (1982)

MCP

	Model MCP Joints (degrees)			
	passive		active	
finger	R.U.D.	F.E.M.	R.U.D.	F.E.M.
Index	71.0	128.5	similar to passive	
Long	72.0	125.0		
Ring	72.0	131.5		
Small	71.0	125.5		

	Human MCP Joints (degrees)			
	passive		active	
finger	R.U.D.	F.E.M.	R.U.D.	F.E.M.
Index	62	155	50	148
Long	53	151	40	145
Ring	55	159	38	149
Small	68	172	57	152

Values for human joints taken from YOUM, Y. et al (1978)
R.U.D.-radius -ulna deviation (adduction / abduction movement)
F.E.M. -flexion - extension movement

Flexor and Extensor Excursion to Flex MCP Joint (mm)	
Model Flexion (FDP)	**Model Extension (EDC)**
18.0	9.5
Human Flexion(FDP)	**Human Extension (EDC)**
21.4 (mean figure)	16.8 (mean figure)

Values for human tendon excursion taken from YOUM, Y. et al (1978)
FDP -flexor digitorum profundus
EDC -extensor digitorum communis

IP

Interphalangeal Joints (degrees)	
Model DIP Joints	**Model PIP Joints**
90	90
Human DIP Joints	**Human PIP Joints**
80-90	110-120

Values for human joints taken from Daniels and Worthingham (1986)

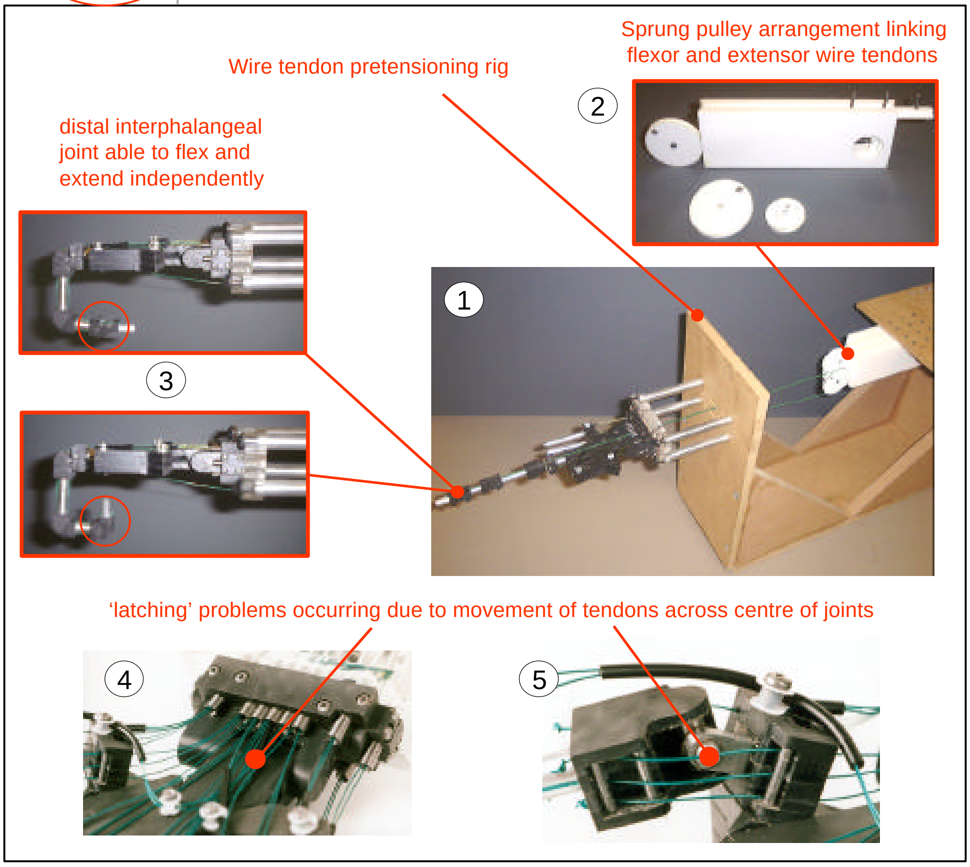


Fig 4.23 Pretensioning Effects on the Skeletal Model Hand

To evaluate the limitations of activating the model joints using wire tendons, it was necessary to build a 'pretensioning rig' to support the model hand and apply tension to the tendons (1).

Wire tendons that were approximations for the flexor digitorum profundus and extensor digitorum communis where linked through tensioning pulley wheels shown in (2). When flexing and extending the finger using this device it was observed that the DIP joint would flex independently to the PIP joint (3). On activation from these tendons in the human hand the DIP and PIP flex and extend together (Kapandji 1982).

Using the pretensioning rig shown it was observed that the use of exclusively extrinsic actuation tendons proves to be problematic when combined with an articulated wrist. It was found that on flexion of the wrist the fingers would extend at at the MCP joint, and the converse would occur on extension of the wrist. Observing the intact hand it is possible to flex and extend the wrist without altering the position of the finger joints. Observation of the tendon excursion for the model fingers when the wrist was moved indicated that a mechanism was required to compensate for the extra tendon excursion required for the wrist if the model fingers were to remain in position.

Additionally, 'Latching' problems were observed when the model tendons were pretensioned. This problem appeared at the MCP and wrist joints. Latching was identified as the joint not remaining in neutral position, instead tending to maximum adduction or abduction. Latching appeared to be caused by the movement of tendons across the centres of these joints in the plane of adduction / abduction (4, 5).

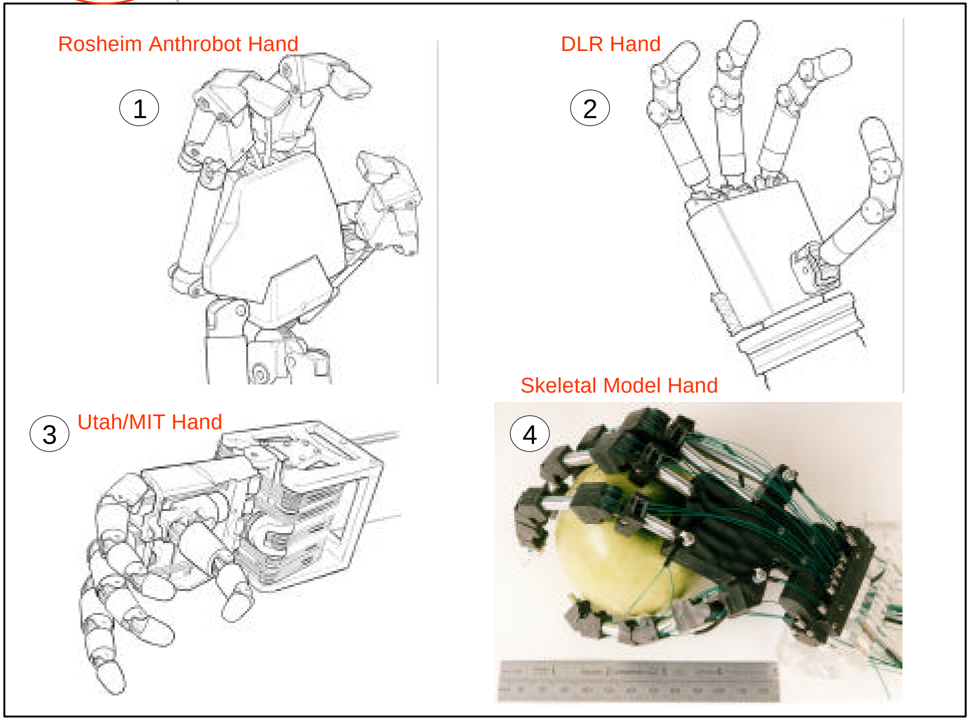


Fig 4.24 Comparisions with Advanced Robotic Hands

The robotic hands (1-3) outlined above are fully actuated devices capable of controlled movement (Rosheim 1994, Herzinger 1995, Perlin et al 1989), whereas the model hand is currently an articulated model with potential for actuation. However, it is appropriate to compare the kinematic design and structure of these advanced robotic hands with that of the skeletal model to inform future cycles of design which must include investigating actuation and control of the model.

Scale

The scale of the skeletal model hand is similar to that of the human hand, as is the Utah/MIT Hand (Jacobsen et al 1984) and the Anthrobot Hand (Rosheim 1994). However, the DLR hand is 1.5 times the scale of a normal hand (Liu et al 1999).

Actuation Stategies

The increase in scale of the DLR hand has been attributed to size constraints of the electric motors which are within the volume of the hand (Liu et al 1999). This is avoided in the Anthrobot hand, as the actuators that move the fingers are on the reverse of the hand (Rosheim 1994). However, this has resulted in a non-anthropomorphic finger design. Actuation comes from ‘extrinsic composite tendons’ in the Utah/MIT hand. Therefore, the large powerful pneumatic actuators to move the fingers are not required to fit within the volume of the hand (Jacobsen et al 1984). However, this approach has been shown to require a more complex control system (Lin and Huang 1996). The model hand may be considered to follow a similar tendon actuation strategy to the Utah/MIT hand.

Joint Kinematics

From the outline drawings it is clear that the skeletal model hand is the only one to possess the anatomical four fingers and a thumb.

The number of fingers has been reduced in the robot hands in part to reduce control system complexity. Historically computational constraints have limited co-ordinated multifinger control (Okada 1982). It has been found however, that manipulation is an essential part of hand function, and this can only be achieved using a minimum of four fingers (Pons et al 1999). Therefore, the Anthrobot Hand cannot easily perform manipulative and regrasping functions. All the hands have fingers jointed in a series - parallel arrangement. This means that as well as permitting rotation in the plane of flexion and extension, the joints also allow adduction / abduction movements. This arrangement has been found to be optimal for both dextrous operations and securing objects within the grasp (Pons et al 1999, Mason and Salisbury 1985). The skeletal model also follows this arrangement of joints.

Both the Anthrobot and DLR Hand share approximately similar finger joint kinematics. The joint nearest the palm on both devices has two actuated degrees of freedom, in the planes of adduction / abduction and flexion / extension (Rosheim 1994, Herzinger et al 1995). On both robotic hands this joint is orientated so that the maximum range of adduction / abduction movements occur when the robotic finger is aligned with the palm. The skeletal model hand follows a similar joint arrangement permitting two degrees of freedom about a single centre point. However, the two degrees of freedom in the Utah/MIT Hand are achieved by two separate joints. One for flexion / extension, aligned in series with the two distal joints, and a more proximal joint whose axis of movement is aligned with the long axis of the palm. This results in maximum adduction / abduction movements in a plane normal to the palm of the hand (Biggers et al 1986). This is a non-anthropomorphic configuration and has been criticised as not permitting some useful hand configurations (Perlin et al 1989).

Joint Placement

The placement of the most proximal joint of the ‘thumb’ has been shown to have a significant effect on the functionality of robotic hands (Perlin et al 1989). Both the Utah/MIT hand and the DLR hand have proximal thumb joints that originate normally from the palm. In the Utah/MIT hand the thumb is placed on the midline of the palm. This was initially due to cable routing, but also supported a desire to produce a single mechanical structure that could be used both for left and right hands (Jacobsen et al 1984). This placement of the thumb prevents the hands from being able to perform a grip on the lateral side of the first finger. Additionally, placement towards the centre of the palm has been shown to limit the robotic hands ability to use certain hand tools (Perlin et al 1989). Both the Anthrobot and skeletal model hand have more anthropomorphically positioned proximal thumb joints.

Coupled Joint Movement

Within the skeletal model hand the distal and proximal analogies of the human interphalangeal joints are motivated by common flexor and extensor wire tendons. This results in the most distal interphalangeal joint flexing before the proximal interphalangeal joint. Within the human anatomy the flexion of these joints is by certain tendons can result in a coupling between the DIP and PIP joints (Kapandji 1982). Like the skeletal model there appears to be no coupling of these distal joints in the Utah/MIT hand. However, Both the DLR and Anthrobot hands couple the movement of these joints. This is achieved in the Anthrobot hand through a rigid link (Rosheim 1994) and through a pulley system in the DLR hand (Herzinger 1996)

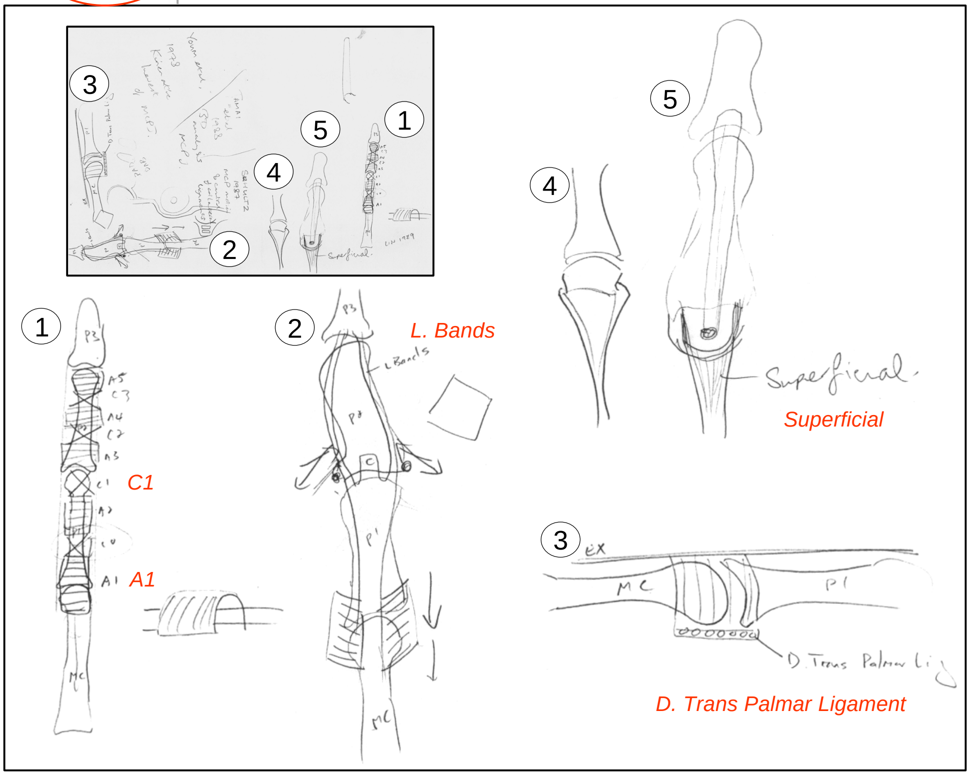


Fig 4.25 Evaluative Sketches Produced by Dr. N. Williams

The model hand was taken to the Royal Hallamshire Hospital for qualitative evaluation by Dr. N. Williams, a consultant hand surgeon with a specialist interest in the development of new prosthetic MCP joint implants. Precedents for this kind of qualitative evaluation for analogy did not appear to exist within this field. However, it appeared appropriate to approach a professional with this specialist knowledge to assess his views on the closeness of the model joints to those of the human hand.

Difficulty had been encountered understanding some of the anatomical literature in the preliminary data collecting stages, due to unfamiliarity with the nomenclature used. It was considered appropriate to take a sketchbook to the interview to allow Dr. Williams to graphically describe his thoughts and observations. Additionally, during the interview Dr. Williams was encouraged to draw tendon routing on the hand of the researcher, again to aid effective communication. These sketches along with notes taken by the researcher at the time represent the record of this evaluation.

The evaluation took place in one of the research laboratories of the Medical Physics department at the Royal Hallamshire Hospital. The interview duration was approximately one hour. It proceeded first by Dr. Williams being presented with the model, then a brief summary of the technical evaluation was given to him. To document this interview notes were taken.

Aims

The stated intentions of the evaluation were for Dr. Williams to assess how closely the analogies of the human joints had been met in the model.

Detail of the Evaluation

(1) Dr. Williams first comment was that for the large number of articulations the model possessed it appeared to be very light, comparable with that of a human hand.

(2) From the palpation of the model IP joints Dr. Williams considered the ranges of movement of the joints to be within the correct range for the normal human IP joint. He added that the IP joints also possessed some lateral movement again similar to that in the human joint IP joint.

(3) He commented that the joints may need to be slightly angled out of line along the long axis of the finger, to enable the fingers to close upon the radial pulse, rather than in the parallel manner that he observed (fig 3.4).

(4) Dr. Williams commented that the silver steel pulleys appeared to work well in combination with the fine steel wire to guide the actuating tendon without it ‘bowstringing’ (fig 3.11). He commented that these appeared a close analogy to the annulus pulley bands such as the one he labelled A1. However, he indicated that within the human hand there are additional cruciate (crossed) bands over the joint itself on the palmar side, which he labelled C1 (fig 4.25(1))

(5) Dr. Williams indicated that the arrangement of tendons that actuate the model finger were not the same as those of the human finger. However, he considered the tendon arrangement effective on the model, and was able to use the tendons to flex and extend the PIP and MCP joints independently. His chief concern was the addition of extra extensor tendons on the model needed to independently flex and extend the MCP joint. He sketched a diagram to show how there is only a single extensor tendon to each of the majority of the digits and each of these tendons split into two lateral bands proximal to the PIP joint (fig. 4.25 (2)) . It was his view that the observed flexing of the DIP independently to the PIP joint was in part due to the diversion of the tendon arrangement to that of the anatomy.

(6) Dr. Williams proposed that problems associated with the model MCP joint latching was again probably due to the tendon arrangement of the model diverting from that of the human anatomy. He indicated that although the interosseous muscles of hand which control adduction and abduction movements of the fingers are inserted into a common extensor hood over the MCP joint, their principle ‘lines of action’ are to the lateral and medial sides of the MCP joint. He added that the dorsal transpalmar ligment is connected medially and laterally to the extensor digitorum communis tendon over the MCP (fig 4.25 (3)). This ensures that the tendon remains aligned towards the midline of the joint, therefore, preventing the latching effects seen in the model.

(7) Dr. Williams highlighted the tendon arrangement on the palmar aspect of the model. The model possesses two extrinsic tendons actuating both adduction / abduction and flexion the MCP joint (fig 4.25 (4)). He indicated that although this arrangement appeared satisfactory for the model, the human superficial flexor tendon infact wraps around the profundus tendon (fig 4.25 (5)). He pointed out that this enables both the extrinsic finger flexor tendons to pass through the MCP joint close to its midline without adversely effecting the adduction / abduction movements of the finger.

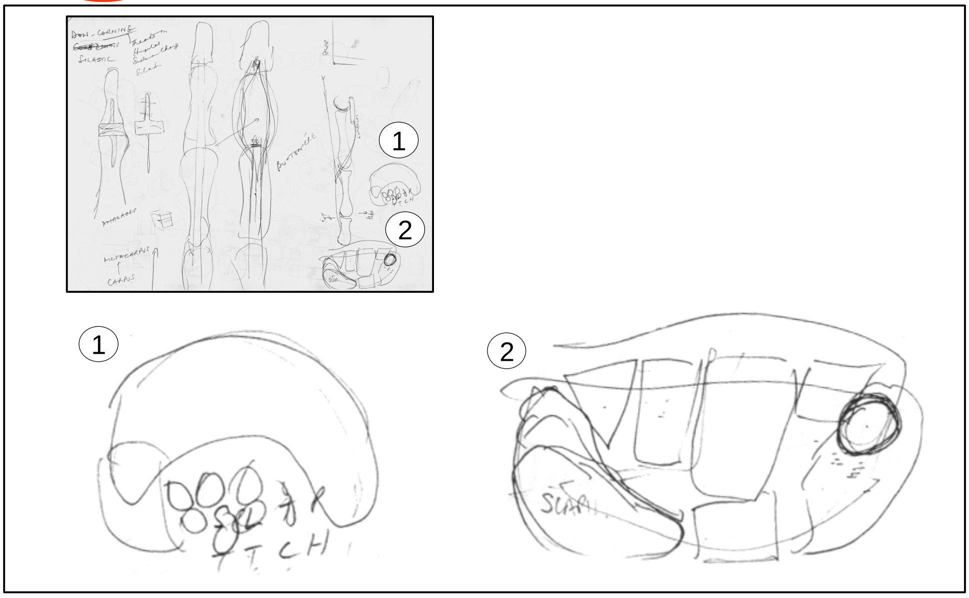


Fig 4.26 Further Sketches Produced by Dr. N. Williams

(8) Palpating the model MCP joint Dr. Williams considered that the joint showed a range of movement that he considered within normal limits in flexion and adduction / abduction. However, he indicated that the joint was able to hyperextend beyond normal limits.

(9) Grasping the model hand Dr. Williams considered that the inclusion of articulations corresponding to the fourth and fifth carpometacarpal (CM) joints was appropriate and anatomically consistent. However, indicated that these joints required constraints as currently the articulations were too ‘mobile’.

(10) Palpating the model thumb, Dr. Williams was content that the two degree of freedom joint at the base of thumb gave the thumb a correct range circumduction. However, pointed out that the placement of the thumb joint could not be accurately assessed due to the unfamiliar form of the model carpus (wrist section).

(11) Dr. Williams was informed of the problems of the wrist ‘latching’ in the plane of adduction / abduction when the extrinsic finger tendons were pretensioned. Dr. Williams indicated that the anatomical carpus is arched in cross-section permitting routing of extrinsic finger flexor tendons close to the centre of the palm (fig 4.26 (1)). He offered that observing the routing of the human flexor tendons might indicate solutions to the latching problem.

(12) From observation of the placement of the sprung guides on the model wrist, Dr. Williams offered that the placement may need adjustment. He offered that the anatomical guides for the extrinsic flexor tendons stretch over the arch of the wrist carpus. He indicated that the anatomical carpal tunnel extends from the trapezium to the hook of hamate (fig 4.26 (2)) .   Therefore, the placement of the flexor tendon guides on the model was too proximal. However, the guides on the reverse of the hand were closer to the placement of the anatomical extensor retiniculum.

Evaluation for Principles Appropriate to a Future Prosthesis

Mr. D. Linford, the commercial manager of Vessa Ltd., was asked to review the model hand. Vessa distribute upper-limb prostheses manufactured by their sister company in the USA. Mr. Linford has more than 20 years experience in the industry, communicating with with prosthetists and user's as well the as managing commercial and technical problems of production.

The review of the model took place in an office at Psalter Lane School of Cultural Studies, Sheffield. Present, other than D. Linford, were the researcher and the supervisors, Prof. A. Wilson and Mr. C. Rust. Notes were taken during the evaluation by both the researcher and the supervisors for subsequent analysis.

The model was presented to D. Linford complete with all its attached wire tendons, however, it was not supported in the pretensioning rig. This was done for demonstration of the potential of the tendon-like actuation of the joints.

Aims

Before the model was presented to D. Linford the aims of the project were outlined. Stressing that analogy to original anatomy had been a key part of the design of the model. Additionally, it was stressed that the model was not intended as a prosthesis in its current form but that the aims of the evaluation were for D. Linford to indicate what he considered were principles within the model that might be appropriate for a future prosthesis.

Detail of Evaluation

Both the researcher and the supervisors had noted the following key points from D. Linford's evaluation of the model:

(1) On first viewing the model D. Linford had remarked on its complexity. Stating key aims principles of successful prostheses was simplicity, and that high complexity and consequently high cost prostheses could not be supported by the current prosthetics market.

(2) From further investigation of the modularity of the joints D. Linfords view of the model changed. He noted that the model was arranged from two joints. His view was that this considerably altered the economic viability of the multi-articulated design.

(3) On pulling the wire tendons he was pleased with the ranges of flexion and extension, and palpating the thumb indicated that its ability to oppose the fingers was important.

(4) His concluding comments were recorded verbatim by the researcher and the supervisors.

'This appears to be the most significant new development in prosthetics since the concept of the myoelectric prosthesis.'

Fig 6.27 Still from Focus Group Video Record

The driving motivation for the project developed from the human needs of the amputee. Therefore, it was considered important to ascertain amputees views on a wide range of topics including the design of a future prosthesis. In particular it was important to how their exposure the skeletal model hand might alter these views.

It was considered appropriate to do this using a focus group format (Krueger and Patton 1988). This was because it was felt that the sensitive nature of the discussion might best achieved using a peer group format (Renzetti and Lee 1993). Additionally, it was felt that from the members selected a diversity of views would be evident and this would add to the evaluation.

The focus group consisted of 13 amputees from the 'Helping Hands' amputee support. There was a male bias within the group, however, this is reflected in the total number of upper-limb amputees (NASDAB 1999). The average age of the amputees attending was estimated at 40 years, this appears to be reflected in national statistics (NASDAB 1999) .

The focus group was organised in accordance with accepted practices, such as appointment of a moderator and reporter (Krueger and Patton 1988). As one of the aims of the focus group was to ascertain aspirations for a future prosthesis it was though appropriate to illustrate some some of the questions for the focus group with clips from Science Fiction. Video clips from The Terminator (Cameron 1984), RoboCop (Verhoeven 1987) and Blade Runner (Scott 1990) were used to illustrate questions surrounding the integration of human and machine components. Factual documentary clips were also used to illustrate ideas of human movement effecting perception (Hennequin 1990, Johnstone 1994 and Disney 1933).

A video-recording was made of the proceedings of the focus group. This video record was replayed for analysis to a group of professionals including representatives from fashion design, furniture design and researchers specialising in anatomy and physiology. This diversity was considered important to obtain an objective consensus on what were considered the salient issues to the amputee. From the video record this could be assessed from both amputees verbal and non-verbal communication (Silverman 1997). The questions posed to the focus group are listed below. These are followed by the findings of the analysis of the video record of the proceeding of the focus group together with relevant quotes.

Focus Group

Questions for Focus Group

(1) *How do you relate to your appliance - as part of yourself or as a tool?*

(2) *In wearing a prosthesis do you perceive yourself as robot-like, or feel others perceive you this way?*

(3) *If you possessed a more hand-like prosthesis would you wear it in a greater range of circumstances?*

(3a) *Would you expect a more hand-like prosthesis to have similar functions to the human hand?*

(4) *Would you prefer to own your prosthesis?*

Analysis of Proceedings

(1) Amputees viewed their existing prostheses as inadequate. They also believed that there was nothing better available and had low expectations for future devices. These views were strongly expressed and reflected a generally negative view of upper-limb prostheses. For example, the technology used in current artificial arms was deemed *'stone age'.*

'I think it is a necessary evil to wear them..'

'I'm always glad to take it <the prosthesis> off….But I like to do things, so I've got to wear it'.

'You have to force yourself to use them'

'It's so obsolete what we've got, that it's not true really, but it is , isn't it.'

'This question here - how do you relate to your appliance - I think, "that bloody thing" and how clumsy it is….At the moment what we've got is a pretty crude set of 50's and 60's tools..'

(2) Individuals in the group indicated that their feelings of separateness to prosthesis could be attributed to lack of confidence in current control methods, and also to uncomfortable suspension methods.

'…when your working with an artificial limb , it's like doubly concentrating for that arm as well as your own arm..to enable you to do a certain job….if you can't do it, you lose self-confidence in that limb and it just becomes a dead weight.'

'It doesn't matter how much it looks like a hand it's not connected to your brain, so you will always have to look at it and concentrate on it..you always have to be looking at what your doing…the first time I used it <cosmetic prosthesis> I stood up went like that <motions swing across table>. Cleared the table of drinks,..it was very embarrassing…I don't wear it anymore.'

'… if it was comfortable it would feel more like you, more like part of you and you'd want to wear it more'

Focus Group Continued

(3) Many amputees made limited use or no use of their prosthesis because of suspension problems and / or an uncomfortable fit.

'… the worst thing for me is discomfort'.

'It's the discomfort of them; it's the thought of putting them on. They rip you to pieces'

(4) The hard surfaces of existing prostheses caused problems, especially when dealing with children.

'You can't play with a child when you've got it on <indicates prosthetic socket> without being scared to death...when I'm playing with my grandchildren I'd rather take my prosthesis off.'

' She <young child> really has hurt herself against that <elbow position of the prosthesis> and I have really cringed…It's really rock hard there'

(5) In order to function 'normally' amputees indicated they need to carry a number of different attachments for their prosthesis and considered this unsatisfactory.

'…it's like walking around with a bag of tools to do one or two different jobs…you need a different appliance to do every job you want to do, It is very difficult to do that'

(5a) Some amputees had made attachments or adaptations for their prostheses and indicated that the ability to adapt the prosthesis was important.

'…I've made that <indicates aerosol cup on end of a split hook to move the gear lever in a car>. I couldn't get anything else to use a manual gearbox car.'

'…I wish I could take that bit of meccano set off and put another bit of meccano set on, that would make it more adaptable.'

'…I have many attachments and I make my own…'

(6) The amputees recognised that natural movement was an essential part of cosmesis. One amputee recounted perceptions when he had viewed himself on video (before viewing the model hand).

'You see a person sat on the bus with their arm like that <arm across lap>…and you think that's an artificial hand.. You watch the way people walk, or the way people sit …I've become quite good at spotting people who wear artificial limbs... We use a video at work. And I've seen myself on that…I've noticed…just how artificial the movement looks, and the way the limb works…your hand has all this flexibility of movement and I just don't think you can replicate that..'

Another amputee shared his comments on viewing a lady with a cosmetic covered myoelectric prosthesis on the introductory video.

'The thing that stuck in my mind was that she hadn't got a wrist, in the prosthesis. And it's obvious to anybody.'

Focus Group Continued

(7) Initially, before introduction of the model hand, amputees were divided between those prioritising function and those prioritising cosmetic prostheses. The group did not expect both needs to be met by a single device.

'..I don't think you can get both <cosmesis and functionality> in one appliance. I think you need two separate ones.'

'..part of the process of losing a limb..coming to terms with it is to see it as a tool…If you hang on to the idea of a replacement limb it's much more difficult to live with it..'

'I see it as a tool and something I have to use to get on with my life.'

'It's a TOOL that's all it is, it's a TOOL'

'I don't really care what it looks like…I'd love to be able to make it work.'

'..from a female point of view, I don't agree with that….I only use it cosmetically and I like it to look part of myself….I've never had anything that does anything and now I'd like one to go out with that looks nice..and one that can help me do various things around the home'

'Mine does nothing...It's got to look cosmetically good for me to wear it….I won't go anywhere without mine. I have to look like everyone else…without it I feel off balance'

(8) The presentation of the model was followed by a change of perception towards the idea that a single device could embody both cosmesis and functionality.

'Ideally you'd <indicating the rest of the group> like it to be cosmetically good and to work properly as well.'

'If your going down, in a new direction, it needs to look cosmetically good and be functional.'

'…I think that's what we should be aiming for...To make something that looks like a hand and functions like a hand, as near as what can be done with the technology that we've got.'

'…There's the cosmetic side and there's practical side, and yes please, we'd all like both...'

(9) Some amputees indicated that their main need was for a cosmetic device, and this was extremely important for their self-confidence. However, one member of the group stated her views had changed since becoming a parent because of the wide range of tasks required for child-care. Arguing that her cosmetic needs required the limb do more for her to appear normal.

'…. I've got a one year old baby and now I could really do with something that does something a little bit more than this <point to cosmetic hand>…Really my worse bit now is that I've got to take her <young child> places where probably every other mum is fully limbed, and I'm not. And I find that people watch how I do things with her, and I could just do with something that this arm <cosmetic prosthesis> would do..'

Focus Group Continued

(10) The group shared her perception that upper-limb prostheses were much less successful than lower-limb prostheses. One user, who also had a lower-limb prosthesis, stated that her artificial leg was satisfactory and met her needs and expectations, however, her artificial arm was very unsatisfactory.

'The legs are fantastic.'

'…legs seem more advanced than arms. Arms seem to have stood still.'

(11) The group showed consensus to paying significant sums of money privately if the a high technology limb replacement was available.

'Anyone would pay a house, the price of a house to get a hand. There isn't anybody here who wouldn't pay that, in fact they'd probably pay twice that..'

'Yes, if it we're available you'd have it.'

(12) The focus group component of the design methodology was seen as positive.

'I think the fact that your coming and asking the people who have to wear them is important. Because I think that generally things were made, then fitted to people, without actually asking the people what their needs were.'

Discussion

Creative Reasoning

The method of design using creative reasoning to extract analogies from the original anatomy has resulted in ideas that when detailed and dimensions are practical for prototype manufacture.

Physical Model Production

The production of models as an integral part of the design process has enabled ideas to be internally evaluated and revised if necessary. An example of this can be seen during the design process. A design concept based around commercially available spherical bearing was rejected when a simple model was made and the comparatively large weight of the components appreciated.

Prototyping Methods

The prototyping methods used appear appropriate for producing the multiple relatively simple joint forms. However, the machining strategies used have resulted in rectilinear forms unlike the complex forms of the human joints. It would appear more appropriate to investigate further prototyping techniques to achieve more complex forms, as well as articulation closer to the skeletal original.

Use of Physical Models for Evaluation

Using the tendon pretensioning rig entirely unforeseen ‘latching and coupling’ effects were observed indicating both closer observation of tendon routing and the limits of mechanical analogy. The coupling problem of wrist and fingers indicates that a mechanical analogy may not be appropriate. Further literature review indicates that this mechanism is controlled in the human by low level synapsing within the spinal cord (Fox 1993). Review of robotics literature indicates that current research is investigating how these mechanisms might be implemented into algorithmns for electronic control systems (Hannaford et al 1995). The pretensioning rig also indicated that a system based on exclusively extrinsic actuating tendons might be prohibitively complex. The literature indicates that current research is underway investigating novel materials that might provide an analogy for the intrinsic’ muscles of the hand (Della Santa et al 1997). Which may lead to simpler control systems.

Comparison with robotic hands indicates that kinematic design principles elucidated in the research may hand an application in a future in telepresence research. As the articulations of the model prove a close match to those of the human ‘master’ control glove compared to the other devices.

Models have played a crucial part in the evaluation of the ‘final’ design. Their use has been valuable in extracting valuable details about where the models are considered to deviate from the anatomy.

From the goniometric data it can be seen that some of the model joints require revision to their ranges of movement to make them a closer analogy to the human joints. This can can be achieved through revisions to the ‘stops’ in the designs without changing their underlying principles of articulation.

The model has enabled expert qualitative criticism on designs, and this has often indicated practical solutions. An example of this came from the evaluation of Dr. N. Williams, who indicated further reference to the anatomy might indicate solutions to the problems of latching of the model joint.

Use of Physical Models for Evaluation (cont.)

This qualitative review was shown to compliment the quantitative assessment of the model joints. For example, the comparisons of the ranges of movement of the model and human MCP joints in of movement data for adduction / abduction are approximately 10 degrees more for the model joint. This can be remedied by simple revision to the joint stops. However, from Dr. Williams qualitative assessment of these joints it was indicated that the human MCP joint exhibited constraint that resulted in a complex path of circumduction, and this was absent in the model. Therefore, indicating more extensive revision of the model MCP joint

Potential for Design Principles to be Embodied in a Future Prosthesis

It has been shown that the resulting model hand assembled from these joints is able to be configured around ‘ergonomically’ designed objects such as door knobs, handles etc. Therefore, in terms of articulation, the model shows functional potential. The hand is of a similar scale to that of a skeletal hand and can be fitted within gloves designed around the dimensions of the human hand. Once inside the glove the fingers can still be flexed using the extrinsic tendons. This suggests a potential cosmetic benefit to the model design.

Review by a prosthetics manufacturer strongly indicated that the modularity of the joints was desirable. His views indicated that modularity may be a means of introducing a new complex prosthesis at a price tolerable to the prosthetics market.

Wider Issues Raised by Focus Group

The model has also has served as a means of changing user’s views. End users previously showing polarised views, in regarding prostheses categorised as either functional or cosmetic, showed their views to be changed by exposure to the model.

The focus group provided the amputees with a forum for which they indicated issues going beyond those posed by the moderator. From the proceedings of the focus group it appeared the design teams (researcher and supervisors) basic assumption that amputees were not happy with existing prostheses was reinforced. However, a key issue to the amputees was the need for a better, and more comfortable means of suspending the prosthesis from their body.

Additionally, it was indicated that the exoskeletal approach to prosthesis deign was not considered acceptable. This was due to unsuitability of the rigid exoskeletal socket. Performing child care activities was indicated as especially problematic due to these rigid surfaces.

This cycle of the research has shown that the creative reasoning process can extract analogies from the anatomy that are practical for prototype manufacture.

The use of CNC processes is appropriate for the production of multiple simple joints.

Design principles appear to be most successful when they are a close analogy of the human joints.